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ENSO and IOD Variability: Impacts on Precipitation and Sea Surface Temperature in Bali and NTB

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This study investigated how interactions between the El Niño–Southern Oscillation and the Indian Ocean Dipole influenced sea surface temperature and rainfall variability in Bali and West Nusa Tenggara. Monthly sea surface temperature, precipitation, and wind data from January 2004 to August 2022 were analyzed using reanalysis and satellite-derived datasets alongside indices of oceanic and dipole variability. Five representative climate phase combinations were identified to capture neutral, wet, and dry conditions. Statistical and spatial analyses demonstrated that coupled El Niño and positive dipole phases produced the strongest cooling of sea surface temperatures (up to 1.2 °C below average) and the most severe rainfall deficits (exceeding 10 mm per day). Conversely, La Niña with positive dipole phases yielded enhanced wet-season rainfall (up to 13 mm per day). These findings showed that phase interactions modulated monsoonal moisture supply, informing water resource management and climate adaptation in coastal Indonesia.

Keywords: El Niño–Southern Oscillation; Indian Ocean Dipole; sea surface temperature; rainfall variability.

1. INTRODUCTION

The Indonesian seas possess unique characteristics due to their strategic location between two major oceans: the Pacific Ocean and the Indian Ocean. These oceans play a crucial role in influencing the dynamics of Indonesian waters, including temperature distribution, current patterns, and marine productivity (Munandar et al., 2021; Adi et al., 2020). Furthermore, climate conditions and seasonal variations are major contributing factors to the variability of rainfall and sea surface temperature (SST) across various regions, including Bali and West Nusa Tenggara. Monthly and seasonal rainfall in Indonesia is predominantly governed by two monsoonal systems: the westerly monsoon, which brings the rainy season, and the easterly monsoon, which brings the dry season. However, the seasonal and interannual rainfall patterns are not always consistent. These inconsistencies are caused by interactions with global climate phenomena, such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which significantly affect rainfall patterns throughout Indonesia (Narulita, 2017; Nabilah et al., 2017; Safitri, 2015; Supari et al., 2018).

The ENSO and IOD phenomena play a significant role in altering rainfall patterns in Indonesia, including in Bali and West Nusa Tenggara. During El Niño events, rainfall variability across Indonesia typically decreases due to the southward shift of the Intertropical Convergence Zone (ITCZ) (Aojie et al., 2023; He-Ming et al., 2022). In contrast, La Niña events enhance rainfall variability through the intensification of the Walker circulation (Wijaya et al., 2023; Habibie & Nuraini, 2014). Meanwhile, negative IOD events often exacerbate drought conditions due to shifts in air currents and cooling of SST in the eastern Indian Ocean, while positive IOD events warm the SST and thereby increase rainfall in the region (Oktaviani et al., 2021; Rahayu et al., 2018; Sri et al., 2021). Previous studies have shown

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that the combined effects of ENSO and IOD on Indonesia's climate are complex and vary regionally and seasonally (Nur'utami & Hidayat, 2016; Nuryanto & Purba, 2019; Satyawardhana et al., 2023).

Sea surface temperature (SST) is one of the key indicators influenced by ENSO and IOD events in the oceanographic dynamics of Bali and West Nusa Tenggara. During El Niño events, SST tends to decrease due to intensified upwelling, which brings cooler subsurface water to the surface. Conversely, during La Niña events, SST increases as surface currents transport warm water masses from the western Pacific into Indonesian waters (Nur'utami & Hidayat, 2016; Srinivas et al., 2022). The IOD phenomenon also has a significant impact, with positive IOD events causing SST cooling in eastern Indonesia due to changes in air circulation and ocean currents, while negative IOD events lead to SST warming as a result of heating in the eastern Indian Ocean (Yustina et al., 2023; Tristianto et al., 2021; Wirasatriya et al., 2017).

Several previous studies have discussed the influence of ENSO and IOD on rainfall variability in Indonesia. Nur'utami and Hidayat (2016) demonstrated that the combined phases of ENSO and IOD substantially affect the spatial and temporal distribution of rainfall across much of Indonesia. Yustina et al. (2023) specifically analyzed the combined influence of the monsoon, IOD, and ENSO in the Mentawai region and West Sumatra, while Rahayu et al. (2018) focused on the impacts of IOD on rainfall over Java Island. Nuryanto and Purba (2019) also reported that positive IOD events can amplify the impacts of El Niño, exacerbating drought conditions in Indonesia, whereas the combination of La Niña and negative IOD has the potential to trigger extreme rainfall. However, studies that explicitly examine the simultaneous influence of ENSO and IOD on rainfall and SST in the Bali and West Nusa Tenggara region remain limited. This study aims to comprehensively analyze the relationship between ENSO and IOD and their impacts on rainfall and sea surface temperature patterns in Bali and West Nusa Tenggara. The findings are expected to provide deeper insights into the interactions between global weather phenomena and local dynamics, as well as their implications for coastal environments and local community activities.

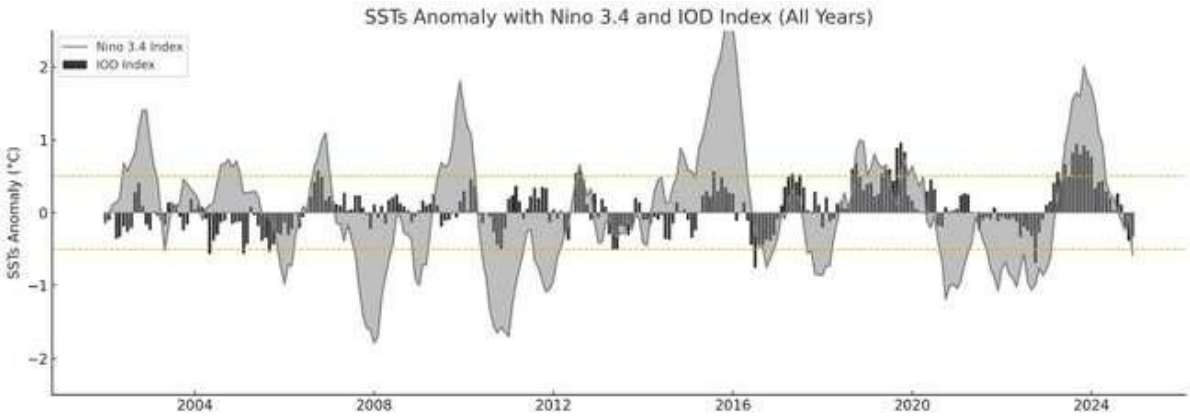

Figure 1. Indices of IOD and Niño 3.4 from January 2002 to December 2022.

2. METHOD

This study was conducted in the waters surrounding Bali and West Nusa Tenggara, a region that exhibits unique characteristics due to its proximity to the upwelling zone in the Indian Ocean (Tristianto et al., 2021) and its susceptibility to global climate variability such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Yustina et al., 2023). The selection of this region was based on the potential significant impacts of global climate phenomena on local weather and oceanographic patterns. A quantitative research approach was employed to analyze these phenomena, encompassing structured processes in data collection, processing, and analysis. Classification of ENSO and IOD events was carried out over the period from January 2002 to December 2022.

The data used in this study consisted of three primary types: sea surface temperature (SST), precipitation, and wind data. These datasets were downloaded from the Copernicus Climate Data Store (ERA5 Monthly Means) https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levelsmonthly-means, with a spatial resolution of 0.25° × 0.25° for atmospheric data and 0.5° × 0.5° for oceanic data. Monthly precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) product with a 0.05° resolution, which has been validated and widely used for tropical climate analyses (Funk et al., 2015). The ENSO variability index was derived from the Oceanic Niño Index (ONI) anomalies based on the Niño 3.4 region, available from NOAA PSL https://psl.noaa.gov/data/timeseries/month/data/nino34.long.anom.data. Meanwhile, the IOD index was taken from the Dipole Mode Index (DMI) anomalies available at https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI. The entire dataset spans 18 years, from December 2003 to August 2022, providing adequate temporal coverage for evaluating the influence of ENSO and IOD on SST and rainfall patterns.

Following Meyers et al., to identify and interpret ENSO and IOD phenomena during the observation period, time series graphs of the Niño 3.4 and IOD indices were presented to visualize the fluctuations in sea surface temperature (SST) anomalies from January 2002 to December 2022 (Figure 1). Based on these graphs, five case categories were defined: Normal ENSO and IOD (2013), La Niña–positive IOD (2007, 2010, and 2022), La Niña–negative IOD (2016), El Niño–positive IOD (2019), and El Niño–negative IOD (2004). The selection of these years considered the relevant variations between ENSO and IOD phases as well as the availability of supporting oceanographic data for analysis.

Data processing was carried out using statistical and spatial analysis methods. The analyses were used to calculate the climatological means of SST, precipitation, and wind patterns based on seasonal divisions: the west monsoon, the east monsoon, and the transitional seasons. The results were visualized in the form of graphs and spatial distribution maps illustrating SST and rainfall anomalies during each phase of ENSO and IOD. This visualization aims to provide a comprehensive spatial understanding of the impacts of global climate variability on the weather and ocean dynamics in the Bali and West Nusa Tenggara region.

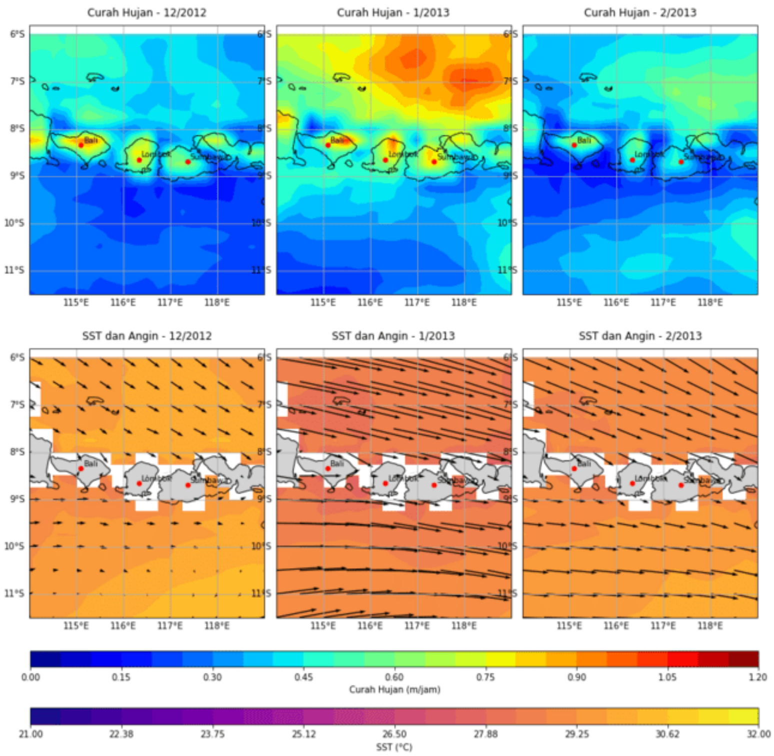

Figure 2. Variations in rainfall and sea surface temperature during ENSO and IOD normal conditions in the western monsoon season of 2013.

3. RESULTS AND DISCUSSION

3.1 Rainfall, Sea Surface Temperature, and Wind Variability During Normal Conditions

Under normal ENSO and IOD conditions in 2013, the sea surface in the southern Bali–NTB region exhibited moderate warm anomalies during both monsoon seasons. During the western monsoon (December–February), Figure 2 shows SST anomalies ranging from +0.3 °C to +0.5 °C concentrated offshore, corresponding with enhanced oceanic evapotranspiration that sustained anomalous rainfall between 6–10 mm/day along the southern coastline, peaking at ~12 mm/day in the Lombok Bay area. This uniform rainfall distribution reflects stable moisture convergence driven by prevailing westerlies. Conversely, during the eastern monsoon (June–August), Figure 3 shows negative SST anomalies from –0.8 °C to –1.2 °C due to upwelling, which suppressed evaporation and reduced rainfall anomalies to below 2 mm/day, with dry pockets reaching –2 mm/day around the Bali Strait. These results demonstrate that under neutral ENSO–IOD conditions, SST fluctuations directly regulate marine moisture availability and rainfall intensity.

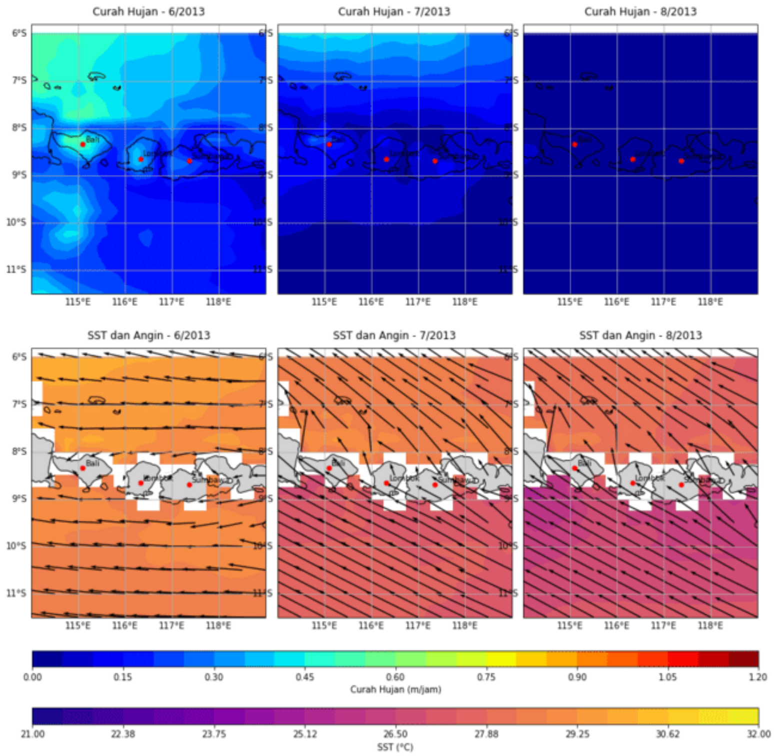

Figure 3. Variations in rainfall and sea surface temperature during ENSO and IOD normal conditions in the eastern monsoon season of 2013.

3.2 Rainfall, Sea Surface Temperature, and Wind Variability During La Niña and Positive IOD

When La Niña coincided with a positive IOD in 2007, 2010, and 2022, SST and rainfall anomalies became more extreme. During the western monsoon, Figure 4 (2007) illustrates SST anomalies of +0.6 °C to +1.0 °C and rainfall of 8–12 mm/day, particularly in southeastern Lombok, indicating enhanced moisture supply driven by intensified Walker circulation. A similar pattern is observed in Figure 6 (2010), with SST anomalies of +0.5 °C to +0.9 °C and rainfall of 7–11 mm/day in southern Sumbawa, although the westerlies weakened slightly. The most intense case is found in Figures 8 and 9 (2022), where SST anomalies reached +0.7 °C to +1.2 °C and rainfall spanned 9–13 mm/day consistently from Bali to NTB, confirming that the combined effects of La Niña and positive IOD maximize oceanic moisture availability. During the eastern monsoon, although Figures 5 (2007), 7 (2010), and 9 (2022) show persistent warm SSTs (+0.3 °C to +0.8 °C), dry easterly winds limited rainfall to only 0–3 mm/day, with dry pockets reaching –3 mm/day. Therefore, the La Niña–positive IOD combination consistently enhances wet season rainfall while mitigating reductions in dry season precipitation across Bali–NTB.

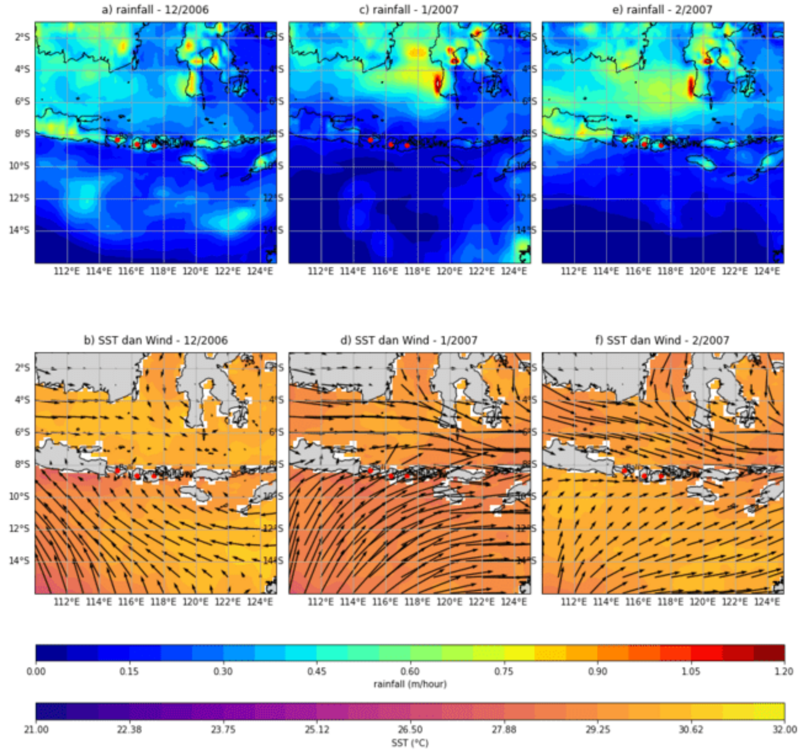

Figure 4. Variations in rainfall and sea surface temperature during La Niña and Positive IOD conditions in the western monsoon season of 2007.

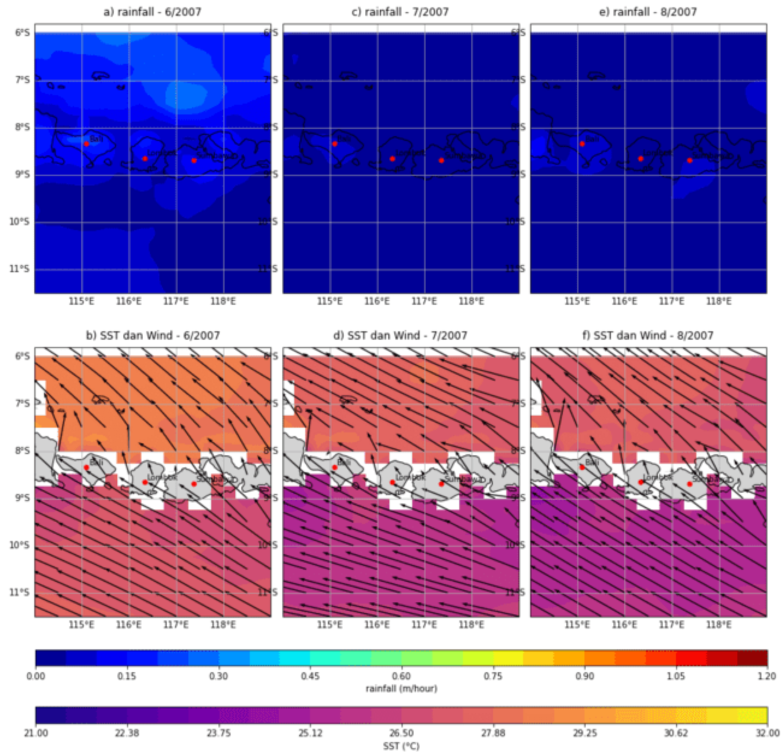

Figure 5. Variations in rainfall and sea surface temperature during La Niña and Positive IOD conditions in the eastern monsoon season of 2007.

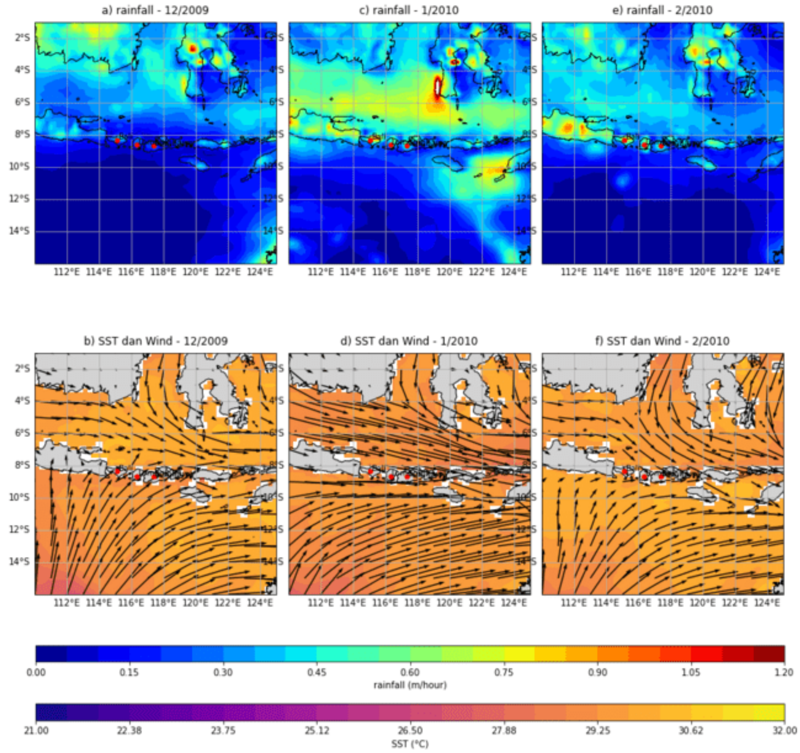

Figure 6. Variations in rainfall and sea surface temperature during La Niña and Positive IOD conditions in the western monsoon season of 2010.

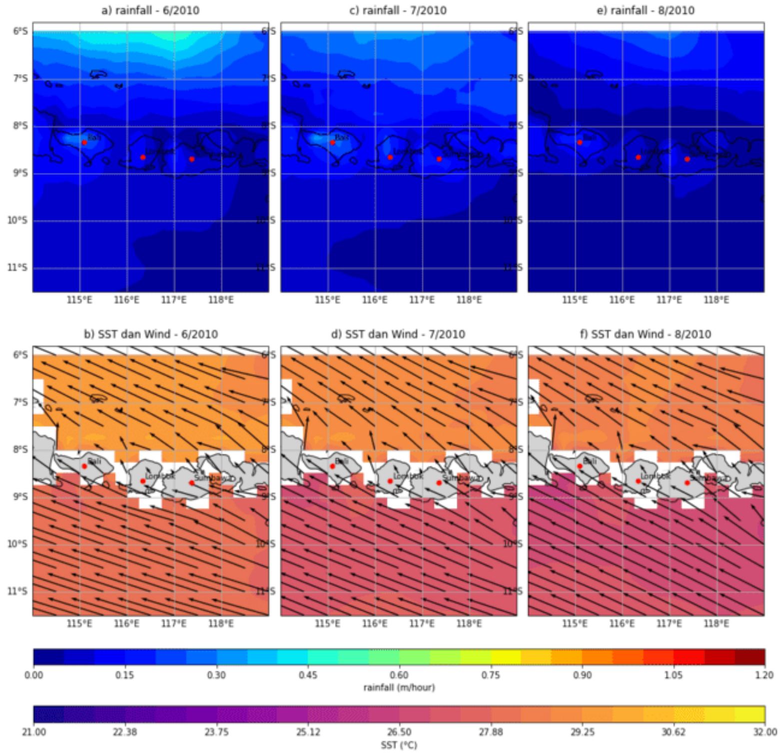

Figure 7. Variations in rainfall and sea surface temperature during La Niña and Positive IOD conditions in the eastern monsoon season of 2010.

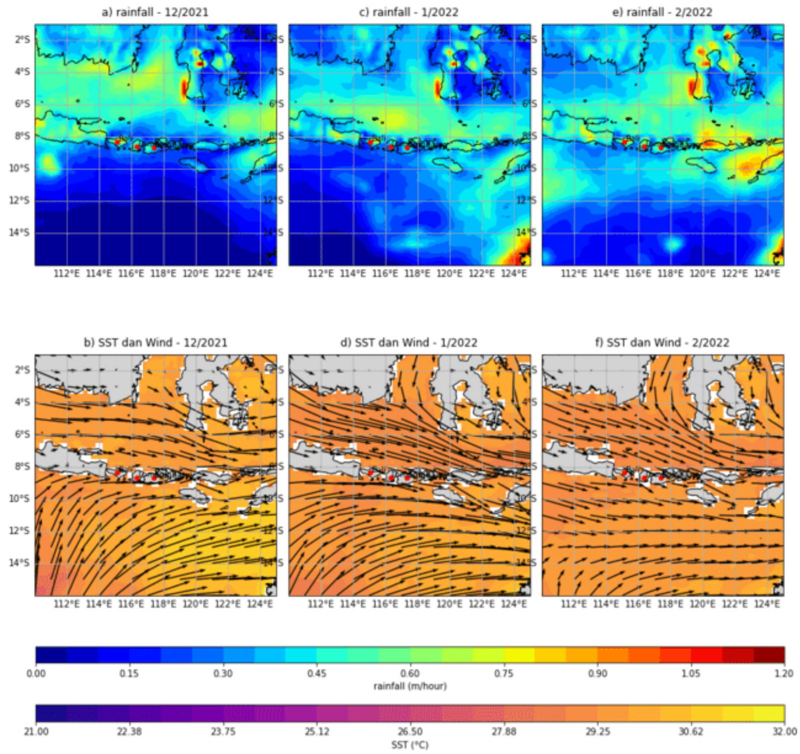

Figure 8. Variations in rainfall and sea surface temperature during La Niña and Positive IOD conditions in the western monsoon season of 2022.

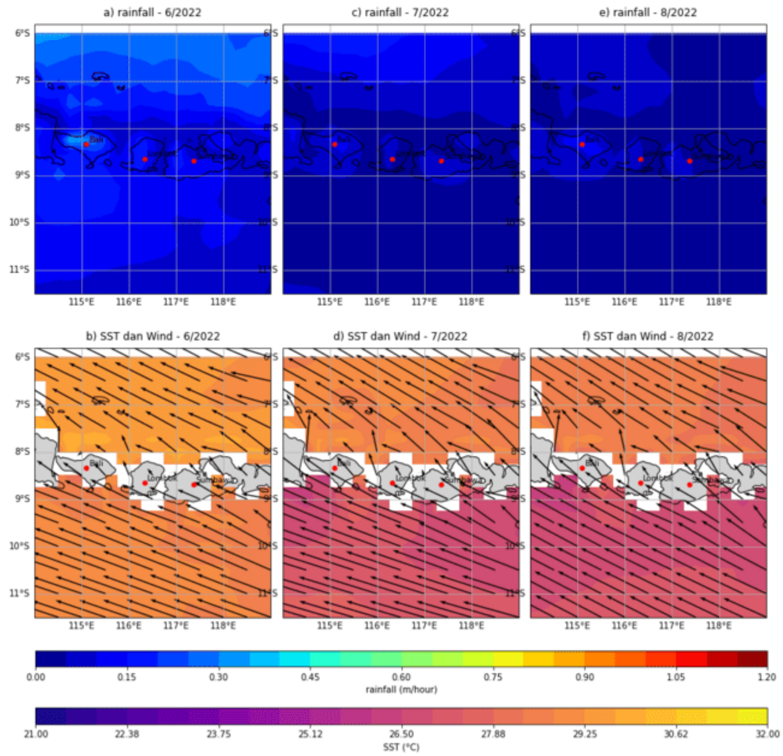

Figure 9. Variations in rainfall and sea surface temperature during La Niña and Positive IOD conditions in the eastern monsoon season of 2022.

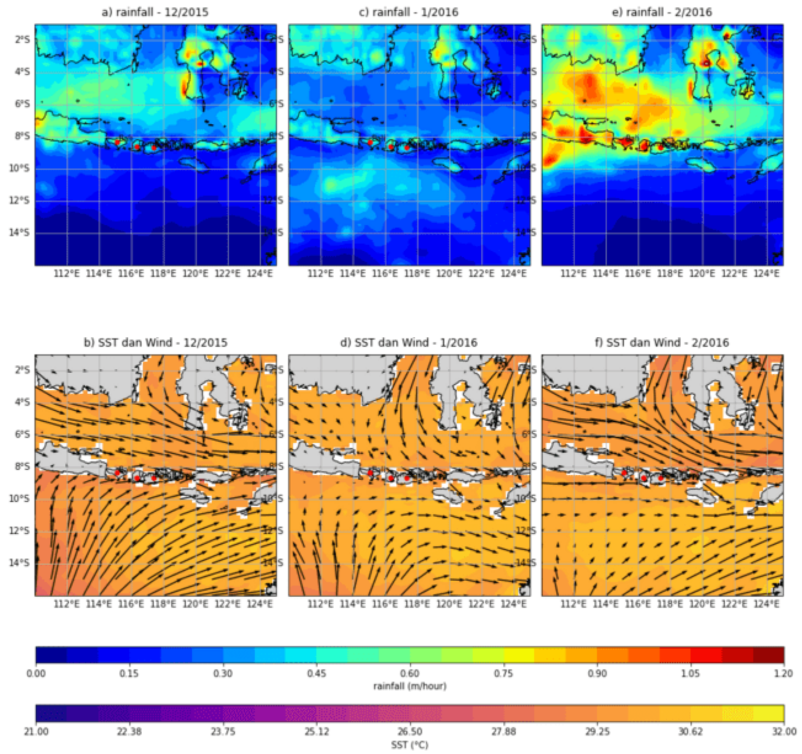

Figure 10. Variations in rainfall and sea surface temperature during La Niña and Negative IOD conditions in the western monsoon season of 2016.

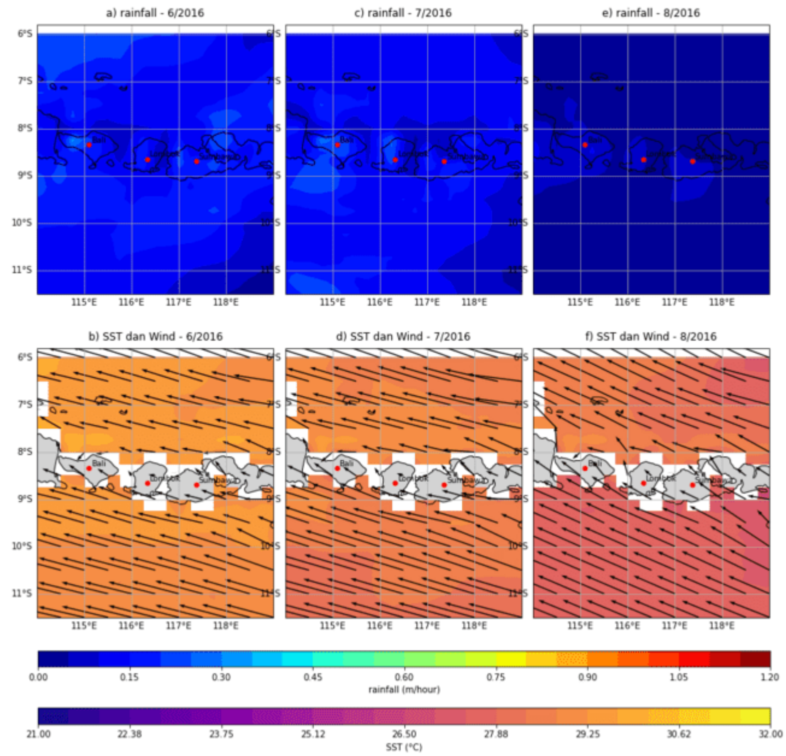

Figure 11. Variations in rainfall and sea surface temperature during La Niña and Negative IOD conditions in the eastern monsoon season of 2013.

3.3 Rainfall, Sea Surface Temperature, and Wind Variability During La Niña and Negative IOD

In 2016, the combination of La Niña and negative IOD resulted in persistently warm SSTs south of Bali–NTB, even during the dry season, with anomalies reaching +0.7 °C to +1.0 °C as shown in Figure 10. This warming enhanced marine moisture content, leading to anomalously high wet season rainfall of +10 to +14 mm/day, especially in Lombok Bay. Entering the eastern monsoon (June–August), Figure 11 shows SST anomalies of +0.4 °C to +0.6 °C, still sufficient to support evaporation, resulting in continued positive rainfall anomalies of +3 to +6 mm/day. The 2016 La Niña–negative IOD event created a “wet” pattern in both monsoon seasons, in which warm SSTs maintained moisture supply despite the presence of dry easterly winds.

3.4 Rainfall, Sea Surface Temperature, and Wind Variability During El Niño and Positive IOD

In contrast, the El Niño–positive IOD event in 2019 caused significant SST cooling south of Bali–NTB, with anomalies of –0.8 °C to –1.2 °C during the western monsoon (Figure 12), leading to suppressed evaporation and substantial rainfall deficits of –6 to –9 mm/day. The eastern monsoon conditions were even more severe, with SST anomalies of –0.6 °C to –1.0 °C (Figure 13), resulting in widespread dry zones with rainfall deficits of –8 to –11 mm/day. This combination produced extremely dry conditions during both monsoon seasons, as indicated by the sharp declines in SST and rainfall depicted in Figures 12 and 13.

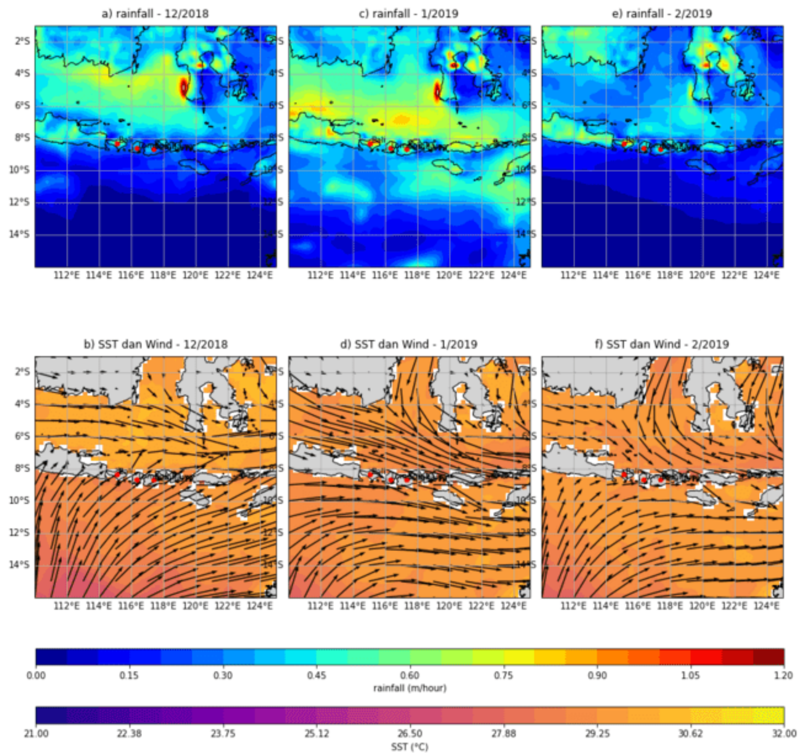

Figure 12. Variations in rainfall and sea surface temperature during El Niño and Positive IOD conditions in the western monsoon season of 2019.

3.5 Rainfall, Sea Surface Temperature, and Wind Variability During El Niño and Negative IOD

In 2004, the El Niño event accompanied by a negative IOD phase led to moderate SST cooling and limited rainfall. Figure 14 (western monsoon) shows SST anomalies between –0.6 °C and –0.3 °C, with rainfall anomalies ranging from –4 to +2 mm/day, where dry pockets were more prominent in Lombok Bay. During the eastern monsoon, Figure 15 shows SSTs from –0.5 °C to 0 °C, and rainfall anomalies from –1 to +3 mm/day, with localized moist zones in southern Bali waters. While El Niño suppressed moisture availability, the negative IOD phase slightly offset the cooling effect, resulting in a relatively dry season with sporadic light rainfall along parts of the coastline.

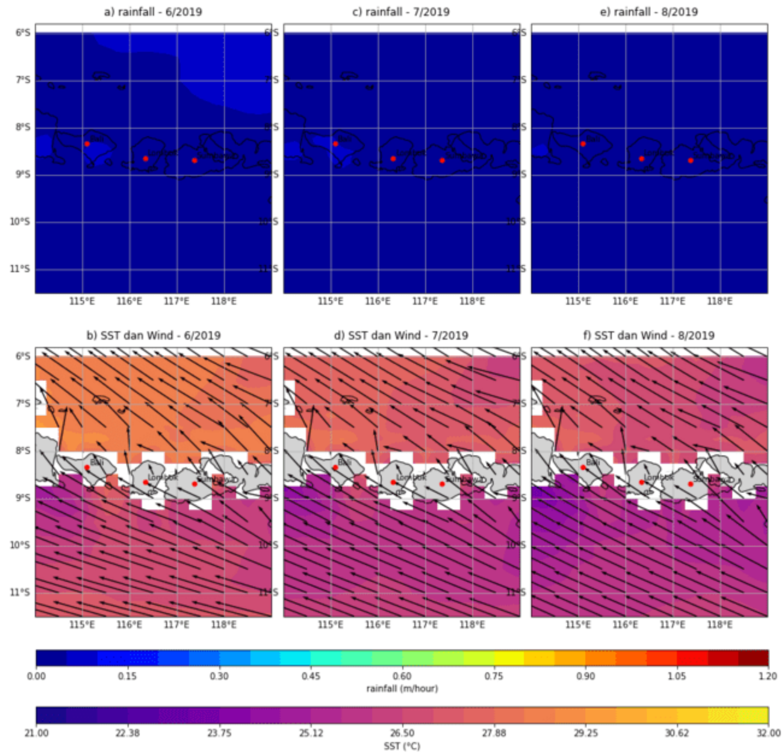

Figure 13. Variations in rainfall and sea surface temperature during El Niño and Positive IOD conditions in the western monsoon season of 2019.

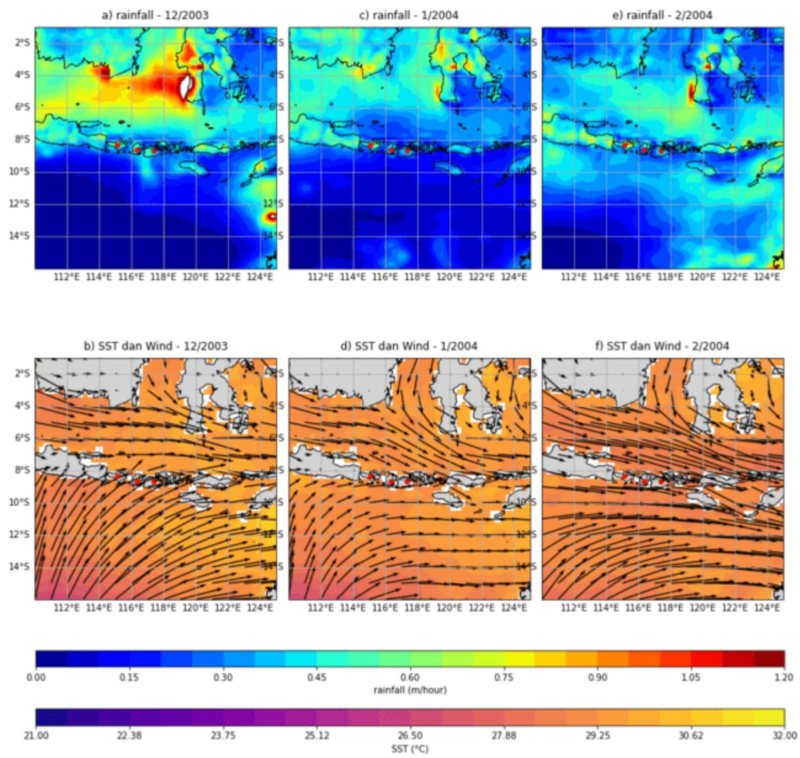

Figure 14. Variations in rainfall and sea surface temperature during El Niño and Negative IOD conditions in the western monsoon season of 2004.

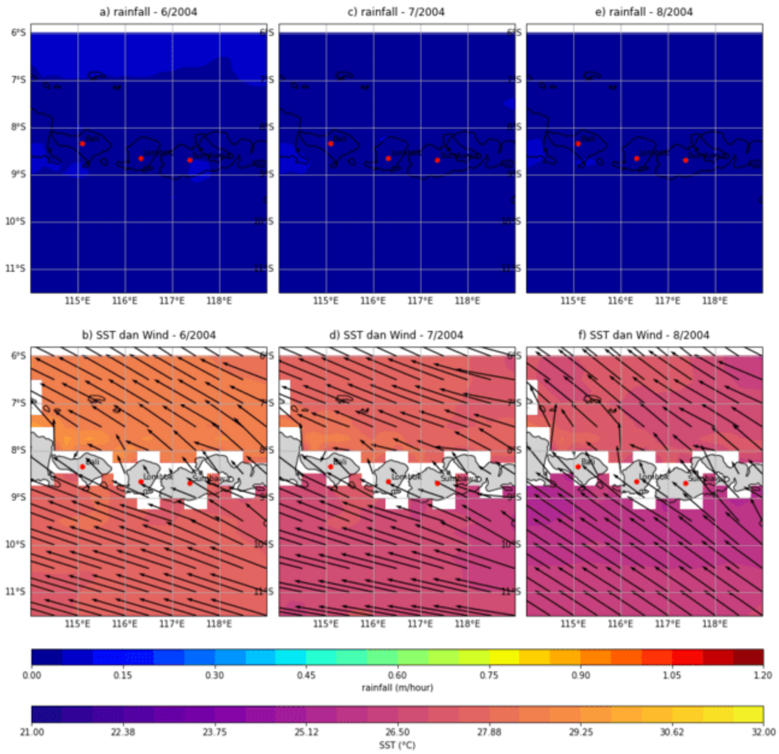

Figure 15. Variations in rainfall and sea surface temperature during El Niño and Negative IOD conditions in the western monsoon season of 2004.

4. CONCLUSION

Based on the analysis of sea surface temperature (SST) and rainfall anomalies in the southern Bali–West Nusa Tenggara (NTB) region across five ENSO–IOD scenarios, it can be concluded that the interaction between these climate phenomena significantly influences monsoonal patterns. Under neutral ENSO–IOD conditions (2013), moderate SST fluctuations (+0.3 °C to –1.2 °C; Figures 3 and 4) directly regulated marine moisture availability, resulting in widespread rainfall of 6–10 mm/day during the wet monsoon and localized dry zones with precipitation below 2 mm/day during the dry monsoon.

During La Niña events coinciding with positive IOD phases (2007, 2010, and 2022), SST exhibited sharp increases (+0.5 °C to +1.2 °C; Figures 5, 7, 9, 10), driving enhanced rainfall of 7–13 mm/day in the wet monsoon season. However, despite persistently warm SSTs, the influence of strong easterly winds during the dry monsoon limited precipitation to only 0–3 mm/day, with dry pockets experiencing deficits as low as –3 mm/day. In contrast, the combination of La Niña and negative IOD (2016) maintained elevated SSTs (+0.4 °C to +1.0 °C; Figures 11, 12) throughout both seasons, sustaining consistently positive rainfall anomalies of +10 to +14 mm/day in the wet monsoon and +3 to +6 mm/day in the dry monsoon.

Under the extreme dry scenario of El Niño with positive IOD (2019), SST cooling was pronounced (–0.6 °C to –1.2 °C; Figures 13, 14), which suppressed oceanic evaporation and resulted in significant rainfall deficits of –6 to –11 mm/day during both monsoonal periods. Finally, in the case of El Niño with negative IOD (2004), moderate SST cooling (–0.3 °C to –0.6 °C; Figures 1, 2) combined with limited moisture recovery associated with the negative IOD phase led to restricted precipitation, with anomalies ranging from –4 to +2 mm/day in the wet monsoon and –1 to +3 mm/day in the dry monsoon.

Overall, the monsoonal patterns in the Bali–NTB region are strongly influenced by the combined phases of ENSO and IOD through SST modulation, which governs the supply of atmospheric moisture. La Niña events coupled with negative IOD phases generate relatively wetter conditions, El

Niño combined with positive IOD phases induces extreme drought, and neutral phases tend to produce more balanced monsoonal climates.

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