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Modulation of the Indian Ocean Dipole on Regional Atmospheric Circulation Variability over the Indonesian Maritime Continent (IMC) across Various ENSO Phases (1991–2020)

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ABSTRACT

This study investigates the modulation mechanisms of the Dipole Mode on the impact of ENSO toward the atmospheric dynamics of the Indonesian Maritime Continent (IMC). Utilizing ERA5 reanalysis and Multi-Source Weather (MSWX) data for the 1991–2020 period, a conditional composite method was applied to 12 climate interaction scenarios. The results indicate that in-phase interactions exhibit constructive interference. The combination of Strong El Niño and Positive DMI triggers massive divergence, leading to "double drought" conditions, whereas Strong La Niña and Negative DMI result in extreme precipitation. A crucial finding confirms the Dipole Mode as a vital modulator. Negative DMI is shown to act as a buffer that mitigates El Niño-induced drought in western Indonesia, while Positive DMI dominantly suppresses La Niña's wet signals. Understanding these mechanisms is essential for the accuracy of seasonal weather predictions and the mitigation of hydrometeorological disasters.

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1. INTRODUCTION

As a strategic country situated between the Pacific and Indian Oceans, and between the continents of Asia and Australia, Indonesia possesses an actively dynamic atmosphere across local, regional, and global scales, which significantly impacts rainfall pattern variations [1]. These atmospheric dynamics are shaped by three primary motions: mean flow, waves, and turbulence [2]. Indonesia is categorized as a Maritime Continent, a region characterized by high convective activity [3], often referred to as the Indonesian Maritime Continent (IMC). Due to its geographical position, the IMC exhibits complex weather and climate conditions [4]. The primary factor driving this complexity is the influence of the Asian and Australian monsoons [5]. Additionally, it is influenced by interannual variability, such as the Dipole Mode [6] and El Niño-Southern Oscillation (ENSO) [7], as well as intraseasonal variability like the Madden-Julian Oscillation (MJO) [8] and synoptic disturbances such as equatorial waves [2]. The interaction of regional dynamics with global variability is crucial, as it can trigger extreme hydrometeorological disasters that threaten public safety [9].

The greatest challenge in analyzing atmospheric dynamics in the IMC is the complex interaction when these phenomena occur simultaneously (co-occurrence), which can be either constructive or destructive. Consequently, weather anomalies in a specific region become difficult to predict if only a single factor is considered [10]. Among these various phenomena, wind circulation and rainfall variability in the IMC are dominantly controlled by global Sea Surface Temperature (SST) anomalies as the primary predictors, specifically the Dipole Mode and ENSO [6], [7]. Prioritizing these two phenomena as the main focus is based on their non-linear interactions, where the Dipole Mode has been proven to significantly modulate the strength of the Walker and Hadley circulations triggered by ENSO [2], [11]. This interaction primarily alters regional wind circulation patterns [12], which subsequently impacts changes in rainfall distribution [1], [13]. Although intraseasonal phenomena such as the MJO also contribute [8], the influence of ENSO and IOD operates on a longer temporal scale and exerts a stronger influence on divergence patterns and low-level moisture transport [9]. Therefore, understanding the modulation mechanisms of these two predictors is vital [9], [10].

Given the vast area of the IMC and the limited number of conventional observation stations, remote sensing and reanalysis data serve as primary solutions [12]. The validity of using satellite-based data to capture extreme phenomena was demonstrated by Saragih et al. (2018), who utilized satellite data to observe rainfall and wind distribution patterns during Tropical Cyclones Cempaka and Dahlia. The utilization of high-resolution data, such as Multi-Source Weather (MSWX) and ERA5, has proven capable of representing spatial atmospheric variability with greater precision than single-point observation data, as validated in various agrometeorological and disaster studies in tropical regions [9], [13], [15]. This approach enables a more in-depth analysis of causal relationships, where zonal and meridional wind circulation anomalies are mapped as primary drivers, followed by a spatial analysis of rainfall response [2].

This study aims to determine the response of atmospheric dynamics in the IMC through a composite analysis approach, utilizing ENSO and Dipole Mode indices as predictor variables to observe their impacts on atmospheric dynamics, as indicated by wind circulation and rainfall variability. This systematic approach is expected to clarify the relationship between large-scale circulation disturbances and regional hydrometeorological impacts to support future disaster mitigation efforts [10].

2. RESEARCH METHOD

This research covers the Indonesian Maritime Continent (IMC), bounded by coordinates 90°E – 150°E and 15°S – 15°N. The selection of this domain is based on the characteristics of the IMC as an active convective region that responds to global circulation anomalies [3]. The study spans a 30-year period (January 1991 to December 2020), representing a standard WMO climate normal period, which is representative enough to capture the interannual variability of ENSO and the Dipole Mode [10].

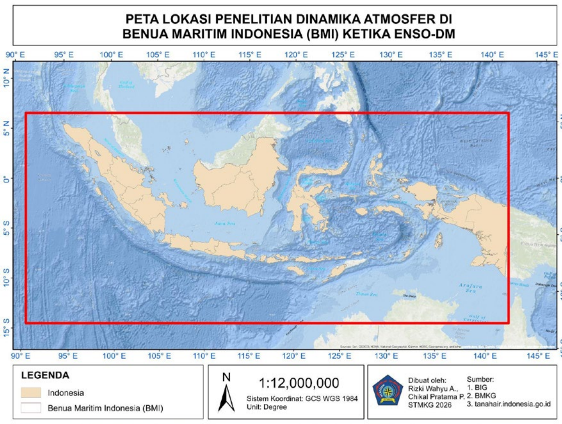

Fig. 1 Study Area Location *(Source: Processed data from the Geospatial Information Agency)*

The data used in this study are secondary gridded datasets, categorized into predictor and predictand variables. The validity of using satellite-based and reanalysis data in tropical regions with sparse conventional observations has been proven effective in previous studies [12], [14].

2.1. Predictor Variables

Predictor variables represent the global-scale climate forcings that drive regional variability:

- Niño 3.4 Index: Used to determine ENSO phases and intensity. Data are sourced from the NOAA Physical Sciences Laboratory, representing Sea Surface Temperature (SST) anomalies in the Central Pacific [7].
- Dipole Mode Index (DMI): Used to determine the phases of the Indian Ocean Dipole (IOD). This index is calculated based on the SST anomaly gradient between the Western and Southeastern Tropical Indian Ocean [6], [11].

2.2. Predictand Variables

Predictand variables represent the atmospheric dynamic responses and hydrometeorological impacts over the IMC:

- Wind Circulation (Dynamics): Zonal (u) and meridional (v) wind components at the 850 hPa pressure level are used to analyze moisture transport patterns and air mass convergence. Data are

sourced from ECMWF Reanalysis v5 (ERA5) with a spatial resolution of 0.25° x 0.25°. ERA5 is considered superior in representing monsoon circulation and atmospheric wave interactions in the tropics [13].
- Precipitation (Impact): Precipitation data are obtained from Multi-Source Weather (MSWX) with a high spatial resolution of 0.1° x 0.1°. This product was selected because it is bias-corrected using global observation stations, providing better accuracy than pure satellite data in mapping rainfall distribution across Indonesia's complex topography [13], [15].

2.3. Software and Tools

- Climate Data Operators (CDO): For processing netCDF data.
- Visual Studio Code: Used for netCDF data processing and generating composite maps using Python 3.10.
- ArcGIS Map 10.8: For creating the study area location map.

2.4. Research Procedures

The method employed is quantitative descriptive analysis with a composite approach. The research stages are as follows:

- Data Collection and Pre-processing: Rainfall (MSWX), wind (ERA5), and climate indices (Niño 3.4 and DMI) for 1991–2020 were downloaded and extracted. Spatial data were then cropped to the IMC boundaries using CDO to optimize computation.
- Anomaly Calculation: The monthly climatological mean (30 years) was calculated for each grid point. Anomaly values were then obtained by subtracting the monthly data from the mean to remove the influence of the seasonal cycle.
- Climate Event Identification: Global index time-series data were categorized based on specific thresholds to determine months falling into the 12 interaction scenarios between ENSO and the Dipole Mode.
- Composite Analysis: An averaging technique was applied to the rainfall and wind data that met the event criteria. The final results are presented as overlay maps to visualize how wind patterns influence rainfall distribution in the IMC.

3. RESULT AND DISCUSSION

3.1. Global Climate Variability Identification

To understand the fluctuations of climate phenomena during the study period, a time-series identification of the Niño 3.4 index and the Dipole Mode Index (DMI) was conducted. The historical visualization of these two indices is presented in Figure 2.

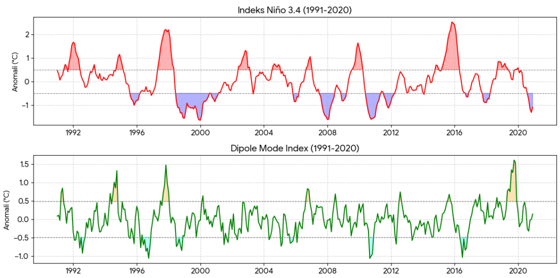

Fig. 2 Time series of the Niño 3.4 index (top) and DMI (bottom) for the 1991–2020 period. Shaded areas indicate active anomaly periods exceeding the established thresholds [16], [17].

3.2. Event Classification Criteria

Composite analysis requires the grouping of events based on their intensity. This study classifies ENSO into six active classes (Weak, Moderate, and Strong for both phases) and the DMI into two active classes (Positive and Negative). The threshold criteria used for these classifications are presented in Table 1 and Table 2.

Table 1. ENSO Phase Classification Criteria

Phase	Category	Index Threshold (°C)
La Niña	Strong	< -1.5°C
	Moderate	-1.0°C to -1.5°C
	Weak	-0.5°C to -1.0°C
El Niño	Weak	+0.5°C to +1.0°C
	Moderate	+1.0°C to +1.5°C

Phase	Category	Index Threshold (°C)
El Niño	Strong	> +1.5°C

Source: Processed data from NOAA, 2024 [16]

Table 2. Dipole Mode Phase Classification Criteria

Phase	Category	Index Threshold (°C)
Positive	IOD (+)	> +0.48°C
Negative	IOD (-)	< -0.48°C

Source: Processed data from Saji et al., 1999 [11]

3.3. Distribution of the 12 Interaction Scenarios

Based on the criteria above, the frequency of occurrences for the 12 combinations of active climate interactions was calculated. The distribution matrix of the number of event months (n) is presented in Table 3.

Table 3. Frequency of ENSO and Dipole Mode Interaction Combinations (1991–2020)

ENSO Category	Positive DMI (n)	Negative DMI (n)
Strong El Niño	8	1
Moderate El Niño	5	1
Weak El Niño	11	1
Weak La Niña	3	7
Moderate La Niña	2	7
Strong La Niña	0	5

Source: Processed data

As shown in Table 3, contrasting interaction patterns are evident. Strong El Niño exhibits a high tendency to co-occur with Positive DMI (n=8); this phenomenon is known as constructive interference, which triggers extreme drought [2]. Conversely, Strong La Niña tends to be associated with Negative DMI (n=5), potentially triggering extreme wet conditions. Combinations of opposing phases (e.g., El Niño with Negative DMI) have a very low frequency of occurrence (n=1), yet they represent critical cases for observing circulation modulation effects [10].

3.4. Spatial Composite Analysis

This analysis presents overlay maps of 850 hPa wind vectors and rainfall for key interaction scenarios.

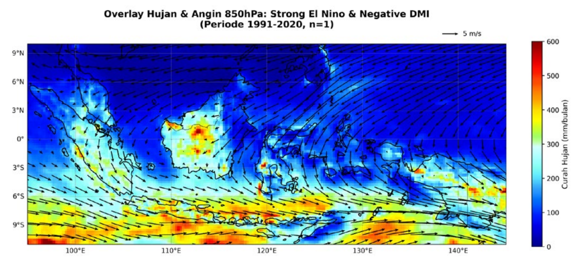

Fig. 3 Overlay Map of Strong El Niño - Negative DMI Configuration

In the Strong El Niño - Negative DMI configuration, the drought intensity typically driven by a strong El Niño is significantly reduced by the wet signal from the negative IOD. Moderate rainfall pockets (200–300 mm/month) are observed persisting along southern regions, including Java, Bali, and Nusa Tenggara. The presence of a Negative DMI triggers westerly wind anomalies south of the equator, transporting moisture from the Indian Ocean and effectively countering the easterly flow from the Pacific. The hypothesized anomaly involves competing forces, where the local warm pool in the eastern Indian Ocean is strong enough to bias the dry Pacific signal, providing natural mitigation against total drought risks.

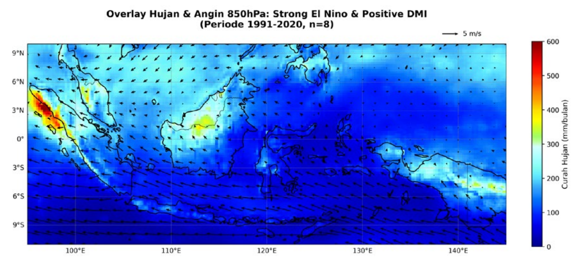

Fig. 4 Overlay Map of Strong El Niño - Positive DMI Configuration

The Strong El Niño - Positive DMI configuration represents an extreme condition that triggers the most severe water deficit anomalies in the dataset. The entire Indonesian Maritime Continent experiences total drought, with rainfall falling below functional ecosystem thresholds (generally <50 mm/month in critical areas). The Walker circulation in both the Pacific and Indian Oceans undergoes a synchronous shift away from Indonesia, creating powerful subsidence (descending air mass). The 850 hPa winds show a highly stable easterly burst, sweeping all moisture toward low-pressure centers in the western Indian Ocean or central Pacific. The hypothesized anomaly is the loss of local variability influence due to the dominance of an overwhelmingly strong large-scale circulation.

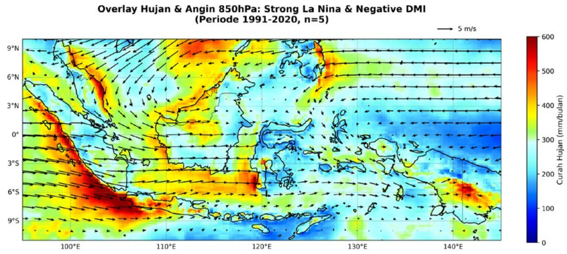

Fig. 5 Overlay Map of Strong La Niña - Negative DMI Configuration

This scenario represents the peak phase of water surplus, often associated with massive hydrometeorological disasters across Indonesia. An overlap occurs between the Pacific warm pool and the warm waters of Western Indonesia, creating intense extra convergence. Rainfall patterns show saturation (red shading, >500 mm/month) across almost all major islands, with very strong westerly anomalies meeting easterly trade winds over the archipelago. The hypothesized anomaly is a massive strengthening of tropospheric humidity up to the upper layers, causing convective clouds to grow deeply and persist throughout the period.

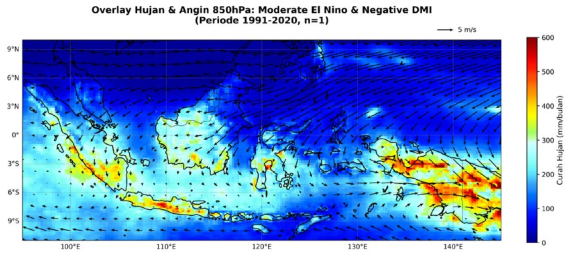

Fig. 6 Overlay Map of Moderate El Niño - Negative DMI Configuration

In this configuration, the drying influence of a moderate El Niño is significantly compensated by the negative IOD. Although low rainfall anomalies occur in central regions, moderate to high rainfall pockets (200–400 mm/month) are still detected, particularly in equatorial regions and Papua. The Negative DMI triggers SST warming in the waters west of Sumatra, dynamically providing additional moisture supply from the eastern Indian Ocean. Circulation analysis at 850 hPa shows that wind patterns are not entirely divergent; instead, westerly anomalies still manage to push moist air masses into the Maritime Continent, ensuring the El Niño drying effect is not absolute and allowing for persistent local rain.

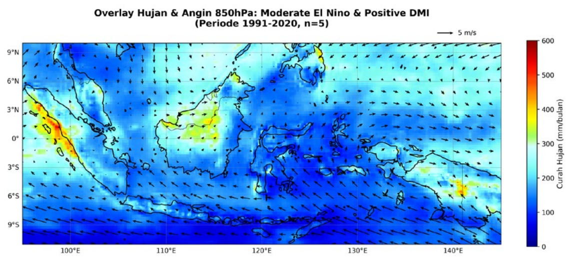

Fig. 7 Overlay Map of Moderate El Niño - Positive DMI Configuration

This scenario represents a dry synergy, where both phenomena work simultaneously to suppress convective activity. A widespread and uniform decrease in rainfall is observed across Indonesia, dominated by dark blue shading (<150 mm/month) covering Sumatra, Java, and Kalimantan. Positive DMI exacerbates dry conditions by cooling SSTs in the eastern Indian Ocean, leading to a drastic weakening of convection. The 850 hPa wind pattern is dominated by strong, divergent easterly flows that mechanically block the formation of convergence zones over the archipelago. Any remaining minor rainfall anomalies are likely products of intraseasonal dynamics (such as the MJO) or strong regional orographic factors, rather than large-scale circulation.

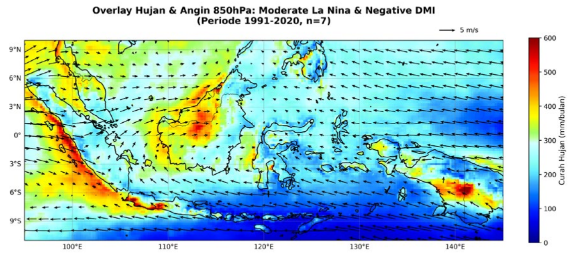

Fig. 8 Overlay Map of Moderate La Niña - Negative DMI Configuration

The combination of Moderate La Niña and Negative DMI creates the most consistent "wet synergy," where Indonesia experiences a significant rainfall increase across nearly all maritime zones. While La Niña enhances convective potential through warm SST anomalies in the Western Pacific, Negative DMI parallelly strengthens the flow of moist air from the Indian Ocean. Visualizations show a broad spectrum of orange to red (>450 mm/month), indicating very high rainfall intensity. The 850 hPa circulation reveals a clear and organized convergence pattern over Indonesia, acting as the primary engine for the massive and sustained lifting of moist air masses.

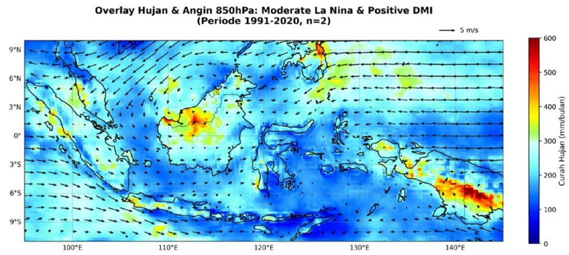

Fig. 9 Overlay Map of Moderate La Niña - Positive DMI Configuration

This condition demonstrates a forced normalization in western Indonesia due to pressure from the positive IOD. Despite an active moderate La Niña, Sumatra and parts of Java show significant rainfall decreases (blue to light green shading). The 850 hPa circulation anomaly shows stable westward wind flow in the Indian Ocean, diverting moisture supply away from the Indonesian coast. The hypothesized anomaly is a shift in regional circulation cells that triggers subsidence in the Eastern Indian Ocean, thereby negating the remote forcing from the Pacific that usually brings abundant rain.

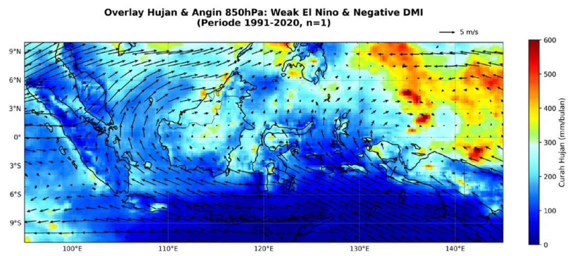

Fig. 10 Overlay Map of Weak El Niño - Negative DMI Configuration

In this configuration, the weak El Niño signal is almost invisible, overwhelmed by the local dominance of the wet-trending negative IOD. The western coast of Sumatra and most of Kalimantan continue to show moderate to high rainfall (green-orange). The 850 hPa wind pattern is dominated by stable westerlies from the Indian Ocean toward the Indonesian landmass. The hypothesized anomaly is that local SST forcing in western Indonesia is far more influential than a weak ENSO signal, maintaining a humid atmosphere that supports daily rainfall in equatorial regions.

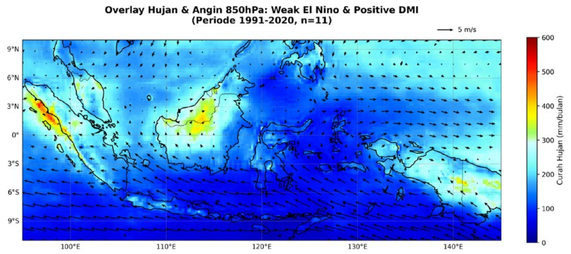

Fig. 11 Overlay Map of Weak El Niño - Positive DMI Configuration

This scenario shows that even a weak El Niño can cause significant drought if accompanied by a Positive DMI. Western Indonesia is dominated by blue shading, indicating uniformly below-normal rainfall. The 850 hPa wind pattern shows fairly consistent easterly flow, though at lower velocities than in strong phases. The hypothesized anomaly suggests that Positive DMI has a low threshold for activating dry conditions in Indonesia, making even a weak El Niño sufficient to trigger widespread water deficits in Sumatra and Kalimantan.

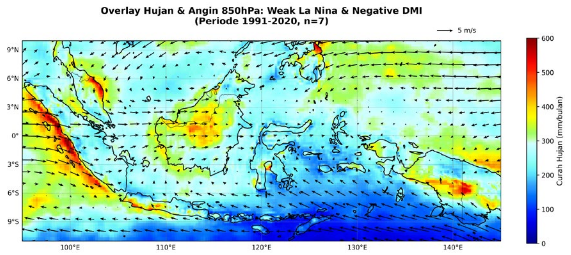

Fig. 12 Overlay Map of Weak La Niña - Negative DMI Configuration

The combination of Weak La Niña and Negative DMI maintains stable wet conditions, especially in coastal and equatorial regions. Rainfall increases appear consistent in northern Sumatra and Papua, with yellow to orange colors dominating the map. Wind analysis at 850 hPa indicates fairly strong local convergence around the Karimata Strait. The hypothesized anomaly is that the interaction of these two phenomena in their weak phases is more influenced by seasonal variability (Monsoon), yet it keeps atmospheric moisture above average, maintaining high rainfall activity.

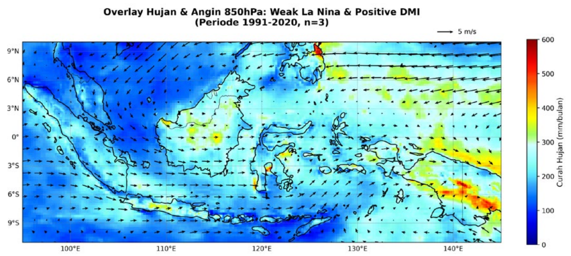

Fig. 13 Overlay Map of Weak La Niña - Positive DMI Configuration

This phenomenon demonstrates that the IOD exerts higher control than a weak ENSO in Western Indonesia. Despite the La Niña (wet) status, the presence of a Positive DMI successfully induces drought in Sumatra and Java. This proves that local forcing from the Indian Ocean can negate remote forcing from the Pacific if ENSO strength is not at a moderate level or higher. The hypothesized anomaly is the inhibition of evaporation in the Eastern Indian Ocean due to cold SST anomalies brought by the positive DMI phase.

4. CONCLUSION

The primary conclusion from the analysis of these 11 ENSO and IOD interaction scenarios confirms that the Indian Ocean Dipole (IOD) plays a more crucial role in determining rainfall variability in Western Indonesia compared to the remote forcing from the Pacific Ocean. The Positive DMI is consistently proven to be a dominant suppressor, capable of neutralizing the wet signals from La Niña phases—particularly at weak to moderate levels—thereby causing significant rainfall deficits across Sumatra and Java. Conversely, the Negative DMI acts as a natural mitigation mechanism (buffer) that reduces the intensity of extreme drought during Strong El Niño events by providing an additional moisture supply from the eastern Indian Ocean.

The interaction between these two phenomena further demonstrates that the influence threshold of a weak ENSO phase is often insufficient to alter Indonesia's regional weather patterns when confronted with an active IOD phase; this indicates that local Sea Surface Temperatures (SST) in Indonesian waters exert more absolute control. In terms of disaster risk, the synergy between Strong La Niña and Negative DMI creates the highest potential hydrometeorological threat through a super-convergence mechanism. Meanwhile, Strong El Niño co-occurring with Positive DMI represents the peak risk configuration for forest and land fires, driven by the total loss of wind convergence zones and a near-complete lack of local evaporation across the Maritime Continent.

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