

**Influences of Indian Ocean Dipole and El Niño–Southern Oscillation on
Thunderstorm Events in Indonesia**

Running title: Influences of ENSO and IOD on thunderstorm events

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Abstract

Understanding the influence of the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) on thunderstorm variability is critical for improving the accuracy of thunderstorm predictions in Indonesia. This study examines thunderstorm variability using nine combination modes of ENSO (La Niña/El Niño) and IOD (positive/negative) derived from the Southern Oscillation Index (SOI) and Dipole Mode Index (DMI) between 1993 and 2022. This study used monthly anomaly gridded flash rate density (FRD) data from 1995 to 2015, and thunderstorm days derived from 3-hourly surface weather reports from the 65 Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) stations from 1993 to 2022.

Previous studies generally show that El Niño tends to increase thunderstorm activity in Indonesia, while La Niña tends to reduce it; however, the precise impacts of their interactions with the Indian Ocean Dipole (IOD) remain poorly understood. This study provides new insights into how combined ENSO–IOD phases drive distinct and regionally varied thunderstorm patterns across the Indonesian archipelago. We demonstrate that La Niña significantly reduces thunderstorm activity when specifically paired with a positive IOD phase, due to weakened moisture transport, cooler surface temperatures, reduced Convective Availability Potential Energy (CAPE), and diminished moisture convergence. Conversely, La Niña combined with neutral or negative IOD phases enhances thunderstorm activity in central and eastern Indonesia through increased moisture availability, surface heating, and atmospheric instability. El Niño typically intensifies thunderstorms in western Indonesia, especially under neutral or negative IOD conditions, driven by increased surface air temperatures and enhanced CAPE; however, El Niño combined with a positive IOD notably suppresses convection nationwide due to decrease surface air temperature, moisture divergence, and reduced CAPE.

Keywords: Thunderstorm, ENSO, IOD, Moisture flux

1. Introduction

A thunderstorm is a weather phenomenon characterised by lightning or thunder accompanying sometimes other severe weather phenomena such as heavy rain, strong winds, hail, and tornadoes. Understanding the thunderstorm activity is important because the thunderstorm affects human safety and causes damages to infrastructure, industry, agriculture, and other human activities. Hoeppe (2016) reported that the activity of thunderstorms worldwide has increased, reaching 300% from 1980 to 2014, resulting in economic losses of approximately US\$ 40 billion in the United States and €7 billion in Europe.

Thunderstorm events in the tropics often occur in tropical land areas, such as Central and South America, Africa, and Southeast Asia, rather than in ocean areas (Dai, 2000; Koloskov et al., 2020; Kotaki and Katoh, 1984; Mezuman et al., 2014). Among the regions strongly affected by thunderstorms in the world, Indonesia has a tropical climate, which is characterised by a high frequency of thunderstorms (DiGangi et al., 2022; Ramage, 1968; Virts et al., 2013a, 2013b). Disasters caused by weather and climatic factors accounted for approximately 80% of the total disasters in Indonesia from 1998 to 2018 and are projected to cause economic losses of approximately US\$ 8.8 billion by 2050 (Haryanto et al., 2019). Therefore, thunderstorm predictions must be strengthened to reduce the impact of thunderstorms and mitigate disasters.

Understanding the influence of global-scale meteorological phenomena on thunderstorm activity is required to improve thunderstorm prediction in Indonesia. The El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are global-scale tropical meteorological phenomena that potentially affect weather and climate variability in Indonesia. Several previous studies showed that warm ENSO (El Niño) reduces rainfall, whereas cold ENSO (La Niña) increases rainfall intensity in Indonesia (As-syakur et al., 2014; Kurniadi et al., 2021; Nur’utami and Hidayat, 2016). On the other hand, there are other studies that showed positive thunderstorm anomalies of the thunderstorm activity in Indonesia during El Niño or warm ENSO periods (Dowdy, 2020; Hamid et al., 2001; Yoshida et al., 2007; Yuan et al., 2016).

These apparently contrasting results of the ENSO impacts on the thunderstorms in Indonesia are obtained as a consequence of neglecting or underestimating the influences of IOD on thunderstorms in different ENSO phases. The combined influence of ENSO and another climate mode in the maritime continent region i.e. IOD on thunderstorms in Indonesia should be considered to provide a comprehensive understanding of thunderstorm development in Indonesia.

The effects of the ENSO and IOD on thunderstorms in tropical regions can be understood regarding surface air temperature, atmospheric moisture and wind patterns. Surface air temperature is a parameter related to the occurrence of thunderstorms, as it is connected to surface heating, which influences updraft energy, indicated by convective available potential energy (CAPE) (Pinto and Pinto, 2008; Price, 2009; Tinmaker et al., 2015). Atmospheric moisture is another important indicator for diagnosing the initiation of deep moist convection, and thunderstorms (Doswell, 2001; Dowdy, 2020; Morrison et al., 2022; Nomura and Takemi, 2011; Sherwood et al., 2010; Takemi, 2014, 2010, 2007). The higher the moisture content, the greater the energy available to support the development and growth of thunderstorms. Previous studies indicated that moisture content is strongly related to thunderstorms (Harel and Price, 2020; Shi et al., 2018; Wahiduzzaman et al., 2022). In addition, precipitable water (PW) is also an effective indicator for identifying high thunderstorm probability in China (Tian et al., 2023). PW and tropospheric humidity characterise the environmental properties of afternoon thunderstorms and mesoscale precipitation systems in Japan (Naka and Takemi, 2023; Nomura and Takemi, 2011; Takemi, 2014; Unuma and Takemi, 2016). Tropospheric humidity also controls the vertical development of moist convection in the tropics (Takemi, 2014; Takemi et al., 2004). In addition, atmospheric circulation also affects the development of thunderstorms and is influenced by ENSO and IOD (Ashok and Yamagata, 2003; Harger, 1995; Kurniadi et al., 2021). Circulation patterns are used to locate areas of convergence and divergence, which also determine the potential areas of cloud growth. Considering the combination of moisture

content and circulation patterns enables us to identify the route of moisture transport toward areas of active thunderstorms.

This study aimed to investigate the combined influence of the ENSO and IOD on thunderstorm events in Indonesia. We specifically extract thunderstorms that accompany lightnings. We used weather report data from meteorological stations for the period 1993–2022 and low-resolution monthly time series (LRMTS) lightning data from the Tropical Rainfall Measuring Mission (TRMM) satellite's lightning imaging sensor/optical transient detector (LIS/OTD) for the period 1995–2014. In addition, we used atmospheric reanalysis data to examine the characteristics of the moisture flux and wind patterns during the ENSO and IOD modes.

2. Data and Methodology

2.1. Flash rate dataset

The monthly anomaly gridded flash rate density (FRD) dataset was obtained from the LIS/OTD 2.5 Degree Low Resolution Monthly Time Series (LRMTS). LRMTS is a dataset constructed from combined data from two lightning detection sensors, the OTD on Orbview-1 and the LIS on the TRMM satellite, from January 1995 to December 2015 with a grid resolution of 2.5°, showing the total flash rates in units of flashes $\text{km}^{-2} \text{ day}^{-1}$ (Cecil, 2006). We then converted the units into flashes $\text{km}^{-2} \text{ month}^{-1}$ by multiplying by 30 days for each grid. A previous study showed that LIS/OTD detection efficiency ranges from 46% to 69% (Boccippio et al., 2000). However, this dataset represents the longest global gridded dataset of lightning observations, making this climatological FRD-gridded dataset reliable for analysing thunderstorm variability.

The monthly anomaly percentage for each gridded FRD dataset was calculated by first removing the seasonal cycle from the monthly FRD time series. This was done by subtracting the first three harmonics of the seasonal signal from the original monthly FRD data. The

resulting values were then divided by the seasonal component and multiplied by 100% to obtain the anomaly percentage for each grid point. This method helps eliminate the influence of the annual cycle, consistent with approaches used in previous studies of climate variability over the Maritime Continent (Lee, 2015; Wheeler and Hendon, 2004). Finally, to reduce the impact of sub-seasonal variability, a 3-month simple moving average was applied to the anomaly percentage data.

2.2. Definition of thunderstorm days (TDAYS)

To address the limitation in detection efficiency of the LRMTS dataset, this study incorporates surface-based observational data to enhance the robustness and accuracy of the analysis. We used 3-hourly surface weather reports from the 65 Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG); and more than 85% of the data from 1993 to 2022 were available, enabling us to define thunder days for each location. This study used a dataset of 3-hourly surface weather reports archived at <https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database> (Smith et al., 2011), which are defined as the code numbers of the World Meteorological Organization (WMO, 2019). For the surface weather dataset, we defined thunderstorm days (TDAYS) as lightning (13), thunderstorms without rain (17), thunderstorms not at observation time (29), and thunderstorms with rain of different intensities and different occurrence times (91–99). Using this definition, we calculated the total accumulated TDAYS for each month at each station. Figure 1a shows a map of Indonesia, comprising of several large islands, such as Sumatra, Borneo, Java, Sulawesi, Maluku, and Papua, and other islands such as Bali and Nusa Tenggara. Although observations from meteorological station weather reports are often sporadic and inconsistent with low observation densities (DiGangi et al., 2022), there is no automatic observation system capable of providing data records for 30 years (such as meteorological station data) to enable analyses of the interannual variability of phenomena such as ENSO and IOD. Therefore, human observations of thunder are critical and must be supported by grid-

based datasets. Figure 1b shows the distribution of the correlation values between the number of monthly TDAYS from meteorological station weather reports and the FRD from the LRMTS from 1995 to 2014. Most locations have a good correlation, with values greater than 0.5 and as high as 0.8, especially at some meteorological stations in southern Indonesia. This correlation value is consistent with previous studies (Lavigne et al., 2019) indicating that the changes in thunder days by human observations significantly correlate (0.88) with the changes in the FRD data from the TRMM LIS satellite in the maritime continent region from 1998 to 2013. Therefore, FRD and TDAYS from the observation dataset were mutually complementary for the analysis conducted in the present study. Calculating the percentage of anomalies for each in-situ observation resulted in a good correlation with the percentage of anomalies in the gridded FRD dataset. Steps to calculate of monthly anomalies percentage on the TDAYS dataset applies the same steps as in the monthly anomaly percentage FRD dataset (section 2.1).

2.3. Determination of ENSO and IOD phases

To determine the phases of ENSO and IOD, we used the Southern Oscillation Index (SOI) (Ropelewski and Jones, 1987) as an indicator of ENSO activity and the Dipole Mode Index (DMI) (Saji et al., 1999) as an indicator of the IOD with the threshold to define a positive (≥ 0.4) or negative IOD (≤ -0.4) (Saji et al., 1999). Meanwhile, to determine warm and cold periods in the ENSO context, we followed the positive SOI threshold above 7 and the negative threshold below -7 provided by the Australian Bureau of Meteorology (Australia Bureau of Meteorology, 2024). The selection of SOI for ENSO identification is based on its more stable and direct relationship with the Indian Ocean Dipole (IOD) compared to Niño3.4, as demonstrated in Kurniadi et al. (2021). The study shows that the SOI–DMI correlation remains consistently negative across all seasons, whereas the Niño3.4–DMI correlation fluctuates, generally positive but turning negative during the March–May (MAM) period. Additionally, SOI better represents atmospheric dynamics during ENSO, while Niño3.4 relies on sea surface temperature anomalies, which can be influenced by long-term warming trends (van Oldenborgh

et al., 2021). Research by Nicholls (2008) also suggests that SOI is more stable in long-term ENSO trends, whereas Niño3.4 exhibits greater variability due to ocean-atmosphere interactions. Furthermore, Niño3.4 is more sensitive to global warming effects, which may amplify El Niño signals and weaken La Niña signals, whereas SOI remains less affected by these biases, making it a more reliable ENSO indicator over long periods

We examined the relationship between monthly TDAYS anomaly or monthly FRD anomaly and monthly ENSO/IOD phases. To obtain a statistical relationship, we calculated Pearson’s correlation (Eq. 1) between the monthly anomalies of TDAYS or FRD and two indices: the SOI and the DMI, which is computed as:

$$r_{xy} = \frac{\sum_{i=1}^n (x_i y_i)}{[\sum_{i=1}^n (x_i)^2]^{1/2} [\sum_{i=1}^n (y_i)^2]^{1/2}}, \quad (\text{Eq. 1})$$

where r_{xy} is the Pearson correlation coefficient, x_i is the monthly TDAYS anomalies of each station or the monthly FRD anomalies, and y_i is the SOI or DMI. The ENSO and IOD phases were combined into nine modes (Table 1). The classification of nine combined modes of ENSO and IOD phases, as shown in Table 1, is based on months that meet thresholds for DMI and SOI in the same month period. Each mode category is separated by specific threshold values for the DMI and the SOI, wherein a DMI (+) juxtaposed with SOI (+) signifies months during which the DMI is at least 0.4 and the SOI exceeds 7. Similarly, other modes reflect combinations of positive, neutral, and negative phases of both indices. This classification ensures that the phases of ENSO and IOD are analysed in the same time period, providing a coherent representation of their interactions and influences on the climate system. We set the confidence level to 95% in the composite process, used the bootstrap method by generating 1,000 random repeated samples to obtain the mean, and found edges at the 2.5th and 97.5th percentiles. We then used the average value between the 2.5th and 97.5th percentiles, with a confidence level of 95%. Bootstrap analysis is a critical method for enhancing the robustness of average anomaly values (Wilks, 2006). The monthly thunderstorm anomaly value with a

significance level of 95% was then composited with the ENSO and IOD periods based on the SOI and DMI.

2.4. ERA5 reanalysis dataset

To analyse atmospheric conditions, this study used ERA5 reanalysis data (Hersbach et al., 2020). Among the dataset, we used the monthly averages of u-component wind (u) and v-component wind (v), the vertical velocity (ω), and the specific humidity (q), mixing ratio (r), surface air temperature (t), and relative humidity (rh) at levels from 1,000 to 200 hPa as well as surface air temperature and convective availability potential energy (CAPE). To follow the resolution of the anomaly percentage of the monthly gridded lightning dataset and to minimise the influence of local phenomena, we upscaled the ERA5 dataset to 2.5° resolution using a bilinear interpolation method. In the bilinear interpolation method, the value of a target grid cell is determined by distance-weighting the values of the four nearest surrounding grid cells. The dataset was then used to calculate the PW by integrating the water vapour content from 1000 to 200 hPa (Salby, 1996):

$$PW = -\frac{1}{\rho g} \int_{1000}^{200} r dp, \quad (\text{Eq. 2})$$

where ρ represents air density, g is gravitational acceleration (9.8 ms^{-2}), and p is pressure. We also calculated the horizontal moisture flux convergence (HMFC) (Banacos and Schultz, 2005; Muhammad and Lubis, 2023) :

$$IHMFC = -\frac{1}{g} \int_{1000}^{200} \left[-u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} \right] dp + \frac{1}{g} \int_{1000}^{200} \left[-q \left(\frac{\partial u}{\partial x} - v \frac{\partial v}{\partial y} \right) \right] dp. \quad (\text{Eq.3})$$

Next, we calculated the monthly anomalies of surface air temperature, CAPE, PW, IHMFC, and wind at the 850 hPa by following steps how to find monthly anomalies of FRD and applying the bootstrap method to obtain the values with a confidence level of 95% at the time of the 9 modes of SOI and DMI combinations.

3. Results

We examined the statistical correlation between the SOI or DMI and monthly thunderstorm events and composite features in each of the nine modes in the IOD and ENSO combinations. With this statistical analysis, we consider the influence of ENSO and IOD on thunderstorm events in Indonesia.

3.1. Relationships of thunderstorm events with ENSO and IOD

To determine the relationship between the monthly thunderstorm events and ENSO and IOD events at each station location, we used the Pearson correlation coefficient with a significance test. According to Yamanaka (2016), positive (negative) SOI values indicated strong (weak) convection in Indonesia, whereas positive (negative) DMI values indicated weak (strong) convection.

In the present correlation analysis, we did not divide the nine modes presented in Table 1. Instead, we directly correlated the number of monthly FRD and TDAYS with SOI and DMI. Figure 2a shows the correlation coefficient between the DMI and the monthly FRD and TDAYS anomalies, indicating that significant positive (negative) correlations dominated in northern (southern) Indonesia. Negative correlations were evidently observed in West Java and southern Sumatra, implying that the responses of thunderstorm events to the DMI differ in the northern and southern regions of Indonesia. A negative DMI was related to more occurrences of thunderstorms in southern Indonesia. The correlation between the DMI and thunderstorms was weaker on the eastern side of Indonesia than in other regions, which appears to be similar to a previous study which indicated that a negative DMI modulated extreme rainfall over southern and western Indonesia (Kurniadi et al., 2021). This finding provides evidence that the IOD, typically associated not only with rainfall variability, but also modulates thunderstorm activity across Indonesia, particularly through spatially contrasting responses between northern and southern regions. Unlike previous studies that focused primarily on rainfall, this research highlights a direct relationship between DMI and observed thunderstorm events, offering new insight into the spatial dynamics of convective responses to Indian Ocean dipole.

The relationships between the monthly anomalies of the FRD, TDAYS, and SOI are shown in Figure 2b. Anomalous lightning days in eastern Indonesia, such as Maluku and Papua, showed a substantial positive correlation with the SOI. Meanwhile, substantial negative correlations were observed in the western regions of Indonesia, such as the northern parts of Sumatra and Kalimantan. Positive relationships between the SOI and thunderstorm events were observed at stations in Indonesia's eastern and central regions. These relationships appear to be consistent with a previous study on the relationship between ENSO and lightning events in Indonesia (Dowdy, 2016). However, this study provides an extended analysis with a spatially explicit perspective across Indonesia, revealing contrasting correlations between SOI and thunderstorm activity in the western and eastern parts of the country.

3.2. Thunderstorm activity in different ENSO and IOD phases

Table 2 presents the number of months for each mode from different combinations of the ENSO and IOD phases during the period available for TDAYS and the period of the FRD availability. The total number of months for TDAYS and FRD availability were 360 and 240, respectively. The positive SOI phase combined with negative DMI occurred for 25 months, while the negative SOI phase combined with positive DMI occurred for 34 months in the TDAYS dataset (1993–2022). In addition, the positive SOI phase combined with positive DMI occurred for 9 months, and the negative SOI phase combined with negative DMI occurred for 10 months. For the FRD dataset (1995–2014), these combinations occurred for 16, 14, 8, and 7 months, respectively.

Figure 3 shows the distribution of monthly TDAYS and FRD anomalies in the nine modes with different ENSO and IOD phases. In general, the TDAYS and FRD anomalies exhibit similar increases or decreases across each mode. During periods with positive SOI accompanied by neutral (Figure 3b) or negative DMI (Figure 3c), the percentages of TDAYS and FRD decreased in western Indonesia, particularly over Sumatra and North Kalimantan, and increased in central and eastern Indonesia; this pattern was especially evident during negative DMI

conditions. Conversely, when positive SOI occurred simultaneously with positive DMI (Figure 3a), TDAYS and FRD decreased across nearly all regions of Indonesia.

In El Niño conditions (negative SOI), negative anomalies of TDAYS and FRD were observed in most regions of Indonesia, except in northern Sumatra and Kalimantan during positive DMI and negative SOI (Figure 3g) and in some regions in Sumatra and West Kalimantan during neutral DMI with negative SOI (Figure 3h). In addition, increasing TDAYS and FRD generally occurred west of Sumatra during negative DMI and negative SOI (Figure 3i).

Additionally, previous studies showed that the mature phase of ENSO occurs from December to February (DJF) (Ham and Kug, 2014; Zheng et al., 2024), while the mature phase of IOD occurs from September to November (SON) (Tang and Zhou, 2023; Zhang et al., 2022). Further analysis in the supporting information (SP.1) also confirmed that the anomaly distributions in SON tend to be consistent with the annual anomaly thunderstorm distributions for all combinations of SOI and DMI. However, the annual anomaly thunderstorm distributions in DJF, demonstrated in supporting information (SP.2) also show a similar pattern to the annual anomaly, except in the case of negative SOI combined with all DMI modes, where a positive anomaly of thunderstorm frequency appears over most of Indonesia, which differs from the annual anomaly pattern observed in this combination mode.

3.3. Surface air temperature anomaly across different ENSO and IOD phases

Figure 4 shows surface air temperature anomalies for each SOI and DMI mode. During positive SOI and positive DMI, a decrease in temperature occurred across almost all Indonesia. Conversely, when SOI was positive and DMI was negative, there was an increase in surface temperature covering most of Indonesia. Meanwhile, when SOI was positive and DMI was neutral, the surface temperature increase tended to occur in eastern Indonesia, while a decrease was observed in western Indonesia. The widespread surface temperature decreases across

Indonesia correlated with a reduction in the number of TDAYS and FRD during positive SOI and positive DMI.

On the other hand, during negative SOI with all phases of DMI, the increase in surface air temperature tended to be limited to parts of Sumatra and Kalimantan. This corresponded to the increase in TDAYS and FRD, which only occurred in parts of Sumatra and Kalimantan across all DMI modes. Meanwhile, other regions showed a tendency for a decrease in TDAYS and FRD under El Niño conditions. These findings are consistent with previous studies, which showed that increasing/decreasing surface air temperature resulted in increasing/decreasing thunderstorms (Price, 2009; Tinmaker et al., 2015). The increase (decrease) in surface air temperature is related to the increase (decrease) in sea surface temperature (SST) (Kawai and Wada, 2007; Large and Yeager, 2012). Generally, during the La Niña (El Niño) phenomenon, increased (decreased) cloud cover results in reduced (increased) outgoing longwave radiation (OLR), leading to warmer (colder) surface air temperatures (Larson and Hartmann, 2003). However, when positive SOI (indicating La Niña) coincides with a positive DMI, a decrease in surface air temperature occurs across almost all regions of Indonesia.

3.4 Convective instability anomalies

We used CAPE as a measure of convective instability. Figure 5 shows the distribution of CAPE anomalies on 9 modes of DMI and SOI. The distribution of CAPE anomalies corresponds to the distribution of TSDAYS and FRD anomalies. The correlation between CAPE and surface air temperature was observed to exhibit a resemblance to the fluctuation in the frequency of deep moist convection.

In the period of the positive SOI and a negative DMI (Fig. 5c), notable positive anomalies in CAPE, were recorded across nearly all regions of Indonesia, demonstrating a relationship with the spatial distribution of surface temperature anomalies. In contrast, under conditions of a positive SOI with a positive DMI (Fig. 5a), a decrease in CAPE was shown in the regions of Java, Bali, and Nusa Tenggara, while an increase in CAPE was shown in northern Kalimantan

and the sea areas located north of Kalimantan and Sumatra. It is crucial to highlight that the observed increase in CAPE in northern Kalimantan did not align with the increasing of surface air temperature anomalies, anomalies in the numbers of TDAYS, and FRD, all of which exhibited decreasing. In the category of a neutral DMI and a positive SOI (Fig. 5b), an increase in CAPE was identified in Java and eastern Indonesia, whereas a decline in CAPE was noted in northern Sumatra and northern Kalimantan.

CAPE anomalies across Indonesia generally tend to decrease under negative SOI or positive DMI phases, while positive SOI or negative DMI conditions are associated with enhanced instability. These patterns suggest that SOI and DMI may interact either synergistically or antagonistically in modulating atmospheric convective potential. While previous studies, such as Yuan et al. (2016), have linked CAPE and thunderstorm frequency to ENSO phases, they typically relied on single-variable approaches and did not examine the combined impacts of the IOD or the role of surface air temperature. Our findings show that certain ENSO–IOD combinations, particularly negative SOI with neutral DMI, are associated with elevated CAPE that does not correspond to increased thunderstorm activity. The increasing CAPE occurred without a corresponding rise in surface air temperature, thereby limiting its effectiveness in supporting thunderstorm activity.

3.5. Moisture variability and transport in different ENSO and IOD phases

This subsection examines moisture variability as modulated by the nine ENSO–IOD phase combinations. Precipitable Water (PW) anomalies are used to represent the total column moisture available in the atmosphere. Figure 6 illustrates that under positive SOI and either neutral or negative DMI conditions (Fig. 6b–c), PW increased across most regions of Indonesia. In contrast, the combination of positive SOI and positive DMI (Fig. 6a) resulted in a notable reduction in PW over western Sumatra, while eastern Indonesia still exhibited positive PW anomalies.

Conversely, a general reduction in PW was observed during negative SOI phases (Fig. 6g–i), particularly over central and eastern Indonesia. The strongest drying signal occurred under the combination of negative SOI and positive DMI (Fig. 6g). In the neutral DMI and negative SOI mode (Fig. 6h), modest decreases in PW were detected across eastern regions, with relatively smaller anomalies in the west.

When DMI was positive and SOI was neutral (Fig. 6d), reduced PW values were observed over the southern Indonesian region, including Java, Bali, Nusa Tenggara, and southern Sumatra—coinciding with reduced thunderstorm activity in those areas. In contrast, the negative DMI and neutral SOI mode (Fig. 6f) showed enhanced PW values, particularly over southern Sumatra and western Java, corresponding to increased thunderstorm occurrence.

To assess the dynamical contribution to moisture variability, we analysed Integrated Horizontal Moisture Flux Convergence (IHMFC) from 1000 to 200 hPa, alongside 850 hPa wind vectors (Fig. 7). Positive IHMFC anomalies indicate convergence of moist air and enhanced potential for convection, whereas negative anomalies reflect divergence and reduced convective potential. Positive IHMFC anomalies were evident in central and eastern Indonesia under positive SOI with neutral and negative DMI modes (Fig. 7b–c). In these cases, wind anomalies at 850 hPa showed clear convergence from the Indian Ocean and Pacific Ocean, leading to enhanced moisture accumulation over Indonesia.

Under the positive SOI and positive DMI condition (Fig. 7a), anomalous westerly winds from the Indian Ocean displayed divergence near 5°–15°S and 90°–100°E, contributing to negative IHMFC values over western Sumatra. In contrast, convergence between easterly and westerly flows in northern Kalimantan led to localized IHMFC enhancement. Additionally, divergent wind flows from Indonesia toward the Philippines and Australia created a drying tendency across western and central Indonesia, consistent with surface air temperature reduction and suppressed convection.

In the negative SOI phases (Fig. 7g–i), 850 hPa winds generally diverged from the Indonesian region toward both the Indian and Pacific Oceans. For instance, in the negative SOI and positive DMI mode (Fig. 7g), strong southeasterly flow over the southern Indian Ocean contributed to negative IHMFC in Java and southern Sumatra. Under the neutral DMI and negative SOI condition (Fig. 7h), divergence over Papua led to negative IHMFC and PW anomalies in that region, a pattern also observed in the negative SOI and negative DMI mode (Fig. 7i).

In the positive DMI with neutral SOI mode (Fig. 7d), wind anomalies directed toward the Indian Ocean reduced IHMFC in southern Indonesia. Under neutral DMI and neutral SOI conditions (Fig. 7e), IHMFC anomalies were minimal, ranging from 0 to 1 kg.m⁻²month⁻¹ indicating climatologically average moisture transport. Conversely, the combination of negative DMI and neutral SOI (Fig. 7f) was characterized by localized IHMFC enhancement over western Java, southern Sumatra, and central Kalimantan, supporting regional thunderstorm activity.

4. Discussion

Previous studies have generally reported that La Niña tends to suppress thunderstorm activity over Indonesia, while El Niño enhances it (Hamid et al., 2001;(Yoshida et al., 2007); Dowdy, 2016; Yuan et al., 2016). However, our study provides new insights by extending this understanding to include the combined influence of the Indian Ocean Dipole (IOD) through nine modes of SOI–DMI phase combinations, where SOI is used as an indicator of ENSO and DMI as an indicator of IOD. We found that the reduction in annual thunderstorm activity over Indonesia region during positive SOI conditions (La Niña) is most pronounced when only coupled with a positive DMI. This combination weakens the easterly moisture transport from the Indian Ocean toward Indonesia, resulting in decreased surface air temperature, reduced CAPE values, and weaker moisture convergence over the region. In contrast, when positive SOI is combined with either neutral or negative DMI phases, increased annual thunderstorm

activity is observed particularly over eastern and central Indonesia. These conditions are associated with surface air temperature increases and low-level wind convergence over the maritime continent, which facilitates moisture transport into the region. This is further supported by positive anomalies in PW and CAPE, indicating a more favorable environment for deep convection.

On the other hand, although El Niño conditions are often associated with increased thunderstorm frequency in Indonesia, our study reveals that this annual enhancement is not spatially uniform across the archipelago. The increase in annual thunderstorm activity during negative SOI (El Niño) is primarily confined to the western region of Indonesia across most DMI modes. Importantly, the extent of this enhancement is strongly modulated by the concurrent phase of the Indian Ocean Dipole (IOD). When negative SOI is combined with either negative or neutral DMI phases, thunderstorm activity extends slightly further into parts of Java and Sumatra. This pattern is supported by mildly elevated surface air temperatures, reduced low-level divergence, and positive CAPE anomalies—particularly over West Java and Sumatra—indicating enhanced convective potential under more favorable thermodynamic and dynamic conditions. In contrast, under the combined influence of negative SOI and positive DMI, a reduction in thunderstorm activity is observed across most parts of Indonesia, with the exception of northern Sumatra. This suppression is associated with negative surface air temperature anomalies and divergent low-level wind patterns that transport moisture away from the archipelago. These conditions are further evidenced by negative anomalies in PW and CAPE, collectively creating an unfavorable environment for deep convective development.

5. Conclusion

The variability of thunderstorm events in Indonesia under different combination modes of ENSO and IOD was investigated using weather report data from several meteorological stations in Indonesia over a 30-year period and a gridded FRD dataset from the TRMM satellite with LIS/OTD sensors over a 20-year period, in conjunction with the SOI and DMI. ENSO has

distinct effects on thunderstorm activity in the western and eastern parts of Indonesia, with the influence of ENSO on thunderstorm events weakening from east to west. Conversely, the effect of the DMI on thunderstorm events in Indonesia diminishes for regions further east and north.

Under positive SOI conditions (indicating La Niña), a significant reduction in annual thunderstorm frequency—exceeding 30%—was observed across most of Indonesia, particularly when combined with a positive DMI. This suppression was associated with weakened 850 hPa wind anomalies from the Indian Ocean, divergent wind patterns over the western Sumatra coast, and reduced IHMFC, PW, surface air temperature, and CAPE. In contrast, positive SOI combined with neutral or negative DMI phases resulted in increased thunderstorm activity over central and eastern Indonesia. This enhancement was linked to converging wind anomalies from both the Indian and Pacific Oceans, increased IHMFC and PW, and elevated surface air temperatures and CAPE, while the opposite effect persisted in parts of Sumatra and North Kalimantan.

Under negative SOI conditions (indicating El Niño), an increase in thunderstorm activity (20–30%) was primarily confined to western Indonesia, particularly Sumatra and West Kalimantan. In contrast, central and eastern Indonesia consistently experienced reductions exceeding 20% across all DMI modes. This decline thunderstorm frequency was associated with anomalous low-level wind divergence flowing outward from Indonesia toward both oceans, along with decreased IHMFC, PW, surface air temperature, and CAPE. Meanwhile, the regions with increased thunderstorm activity in the west showed localized enhancements in surface air temperature and CAPE despite neutral PW and IHMFC anomalies.

In the present study, we analysed the influence of ENSO and IOD on thunderstorms by focusing on the impacts of year-to-year variabilities on the environmental properties of thunderstorm environments. However, further studies are needed to understand the combined effects of inter-annual phenomena, such as ENSO and IOD, and intra-annual phenomena, such

as monsoons and the inter-tropical convergence zone (ITCZ) on thunderstorm events in Indonesia.

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Conflict of Interest statement

The authors declare that they have no conflict of interest.

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Authors' contributions

Novvria Sagita: Conceptualization; formal analysis; funding acquisition; investigation – methodology; project administration; resources; software; visualization; writing – original draft preparation. **Tetsuya Takemi:** Conceptualization; funding acquisition; methodology; project administration; supervision; validation; writing – review and editing.

Data availability

The surface observation dataset for Indonesia is available at <https://www.ncei.noaa.gov/access/search/data-search/global-hourly>. The dataset was decoded using the guidelines available at <https://www.ncei.noaa.gov/data/global-hourly/doc/isd-format-document.pdf>. ERA5 data (Hersbach et al., 2020) from the European Centre for Medium-Range Weather Forecasts were downloaded from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form>.

The LRMTS dataset was downloaded from
https://cmr.earthdata.nasa.gov/search/concepts/C1995865015-GHRC_DAAC.html.

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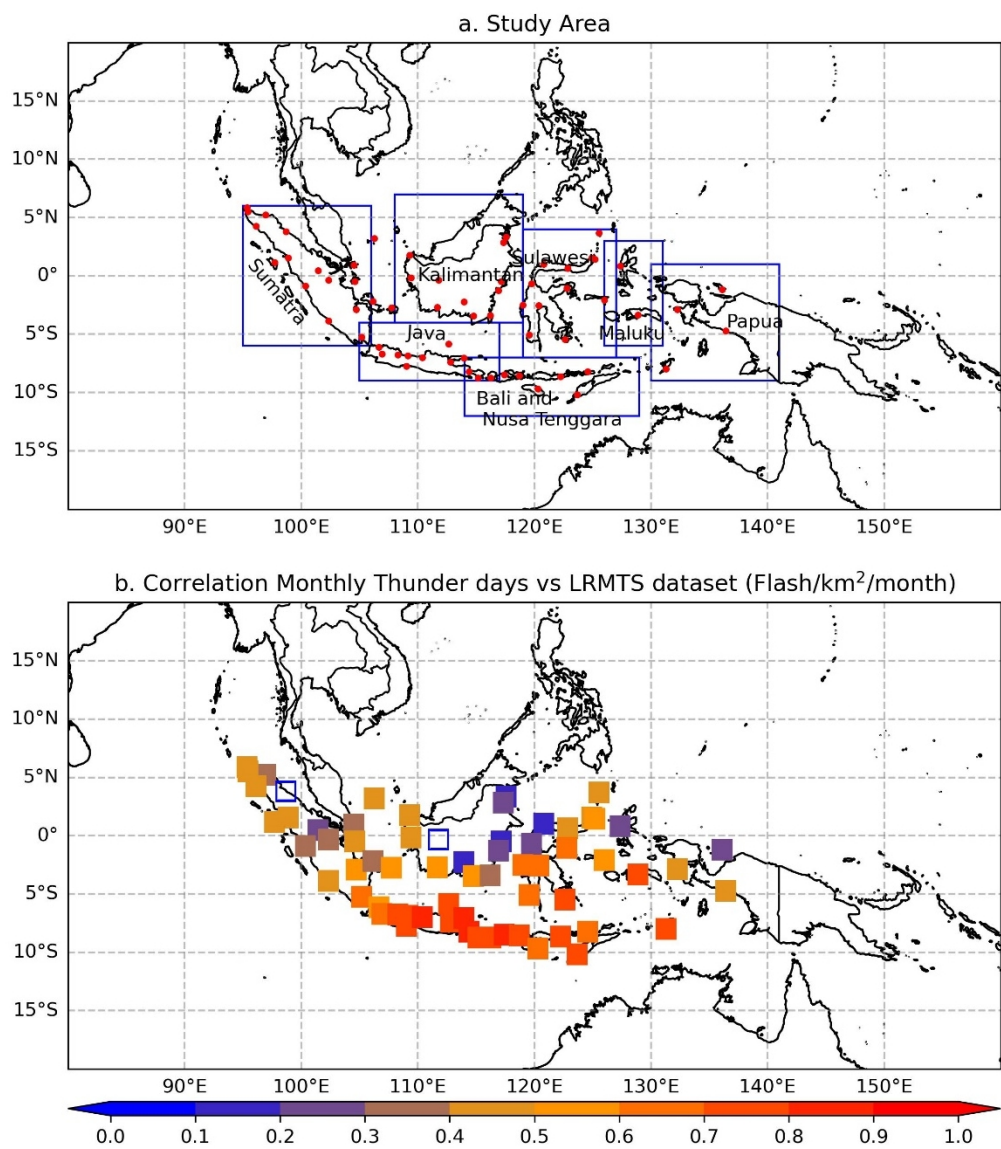


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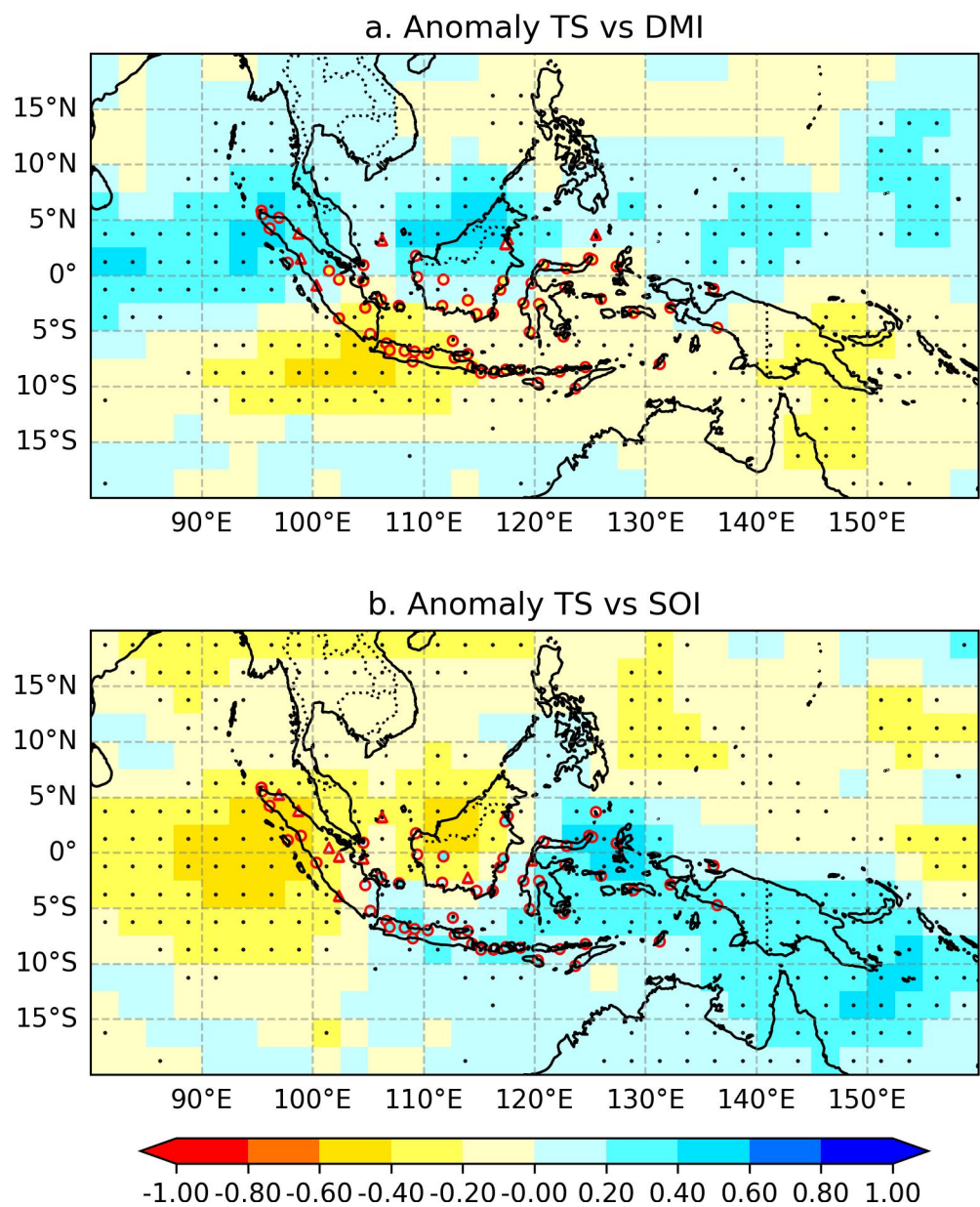


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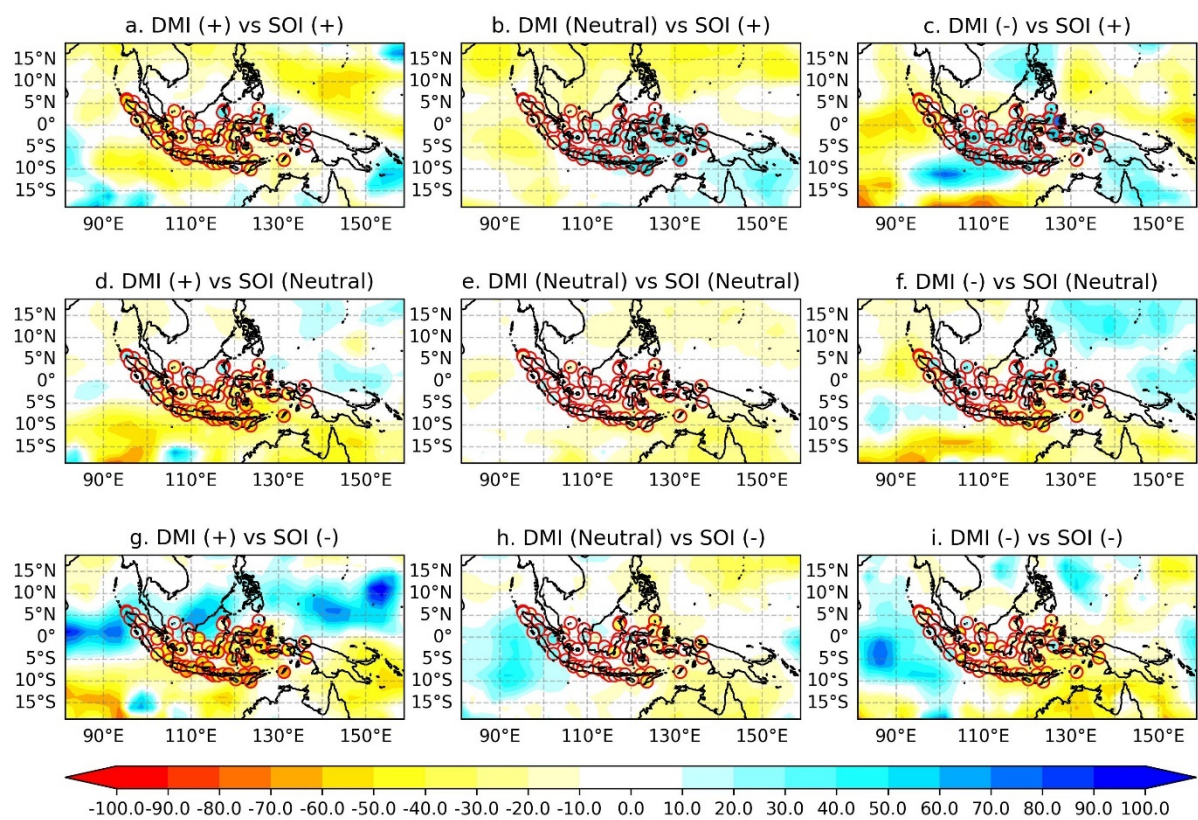


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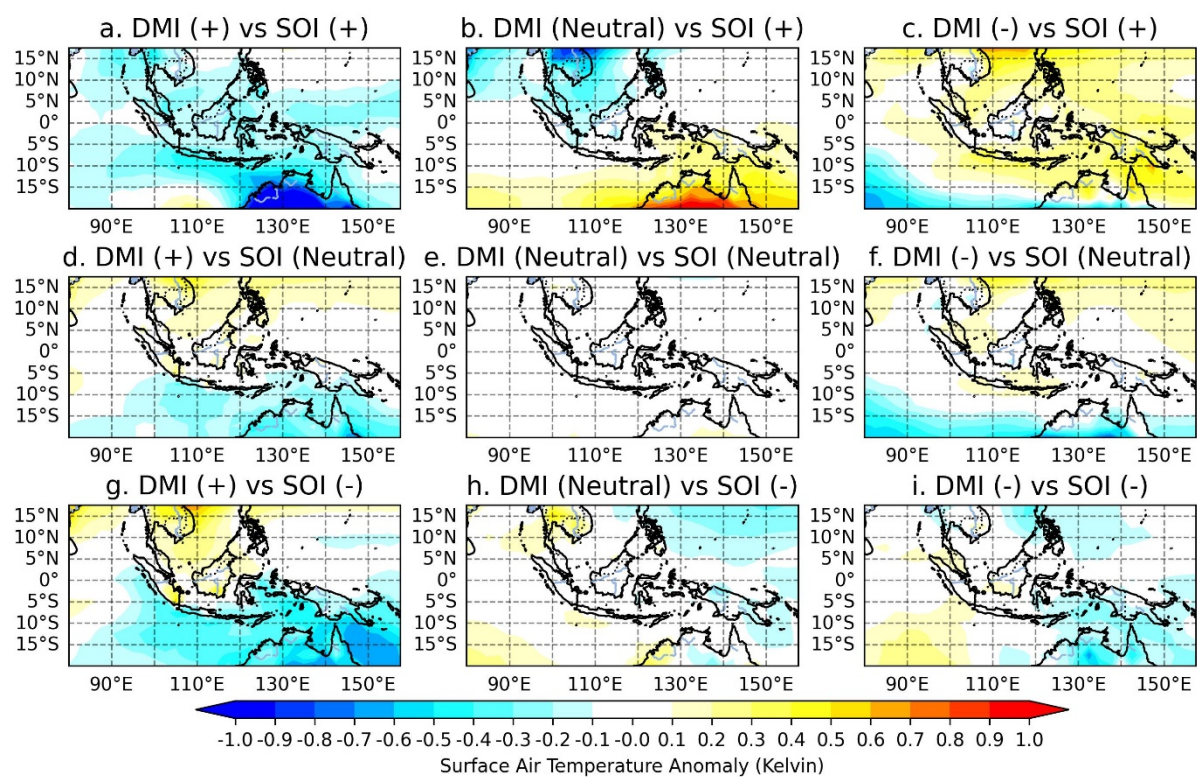


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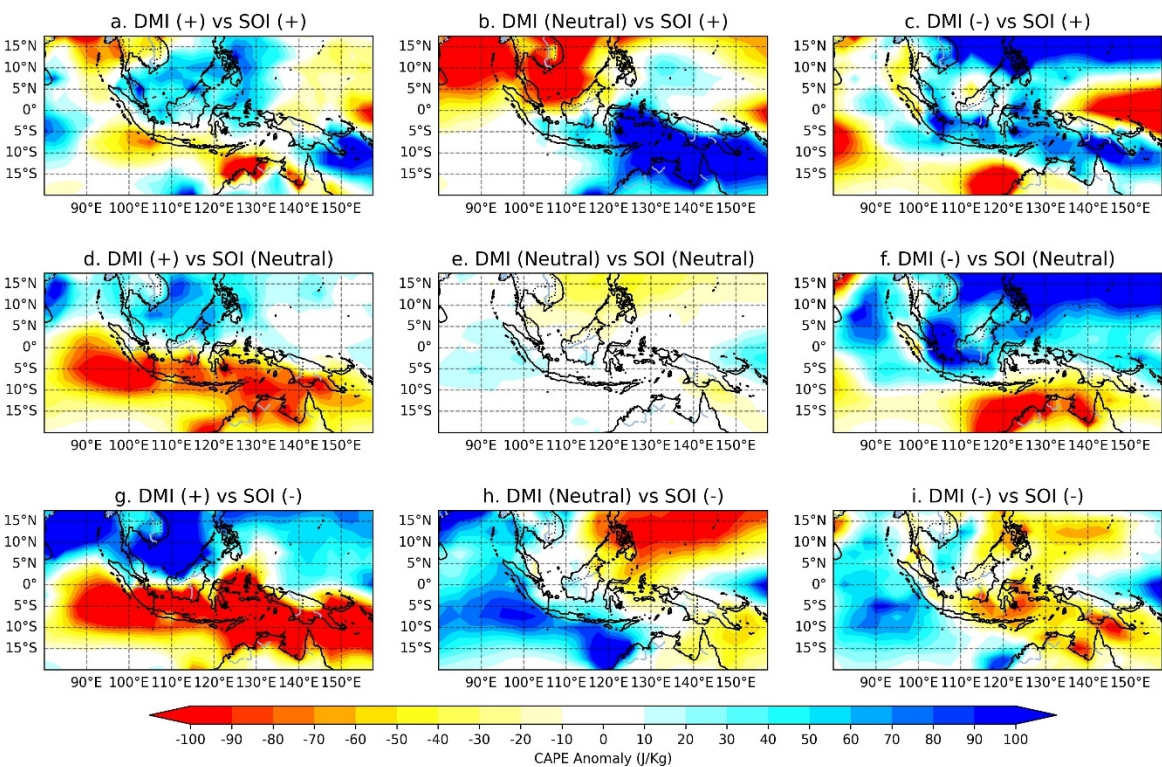


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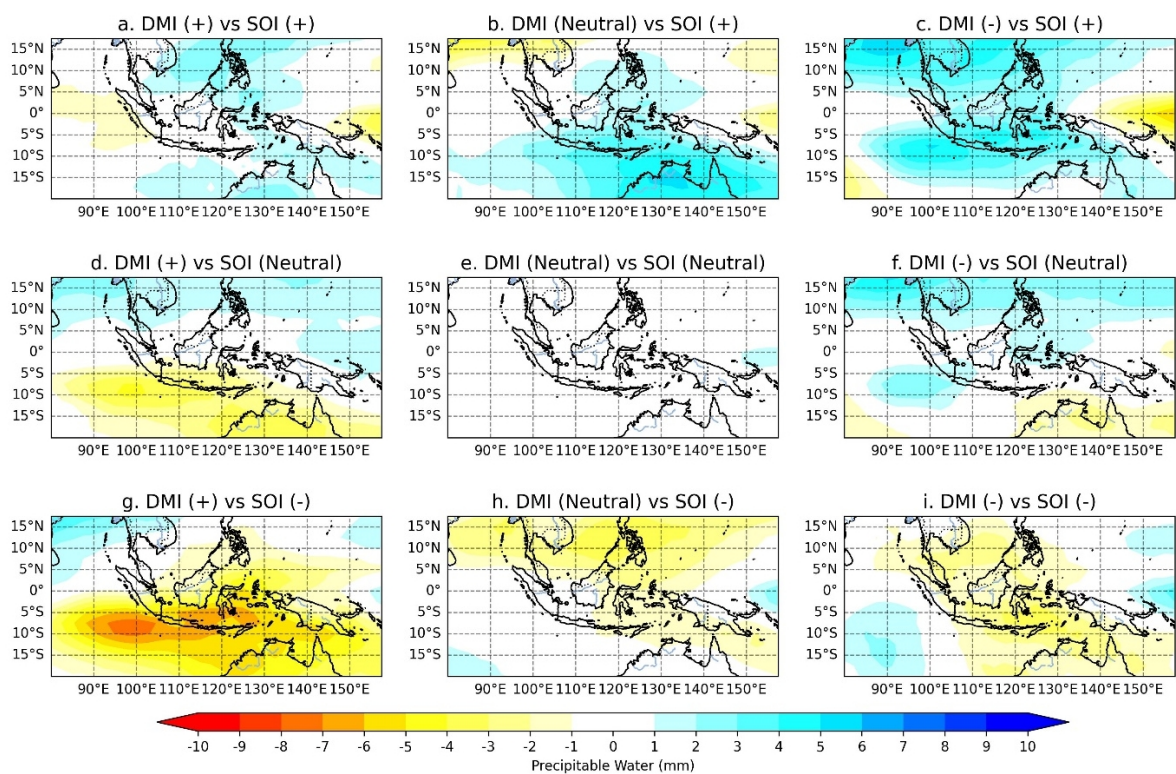


Figure 6. Same as Figure 4, but for PW anomalies.

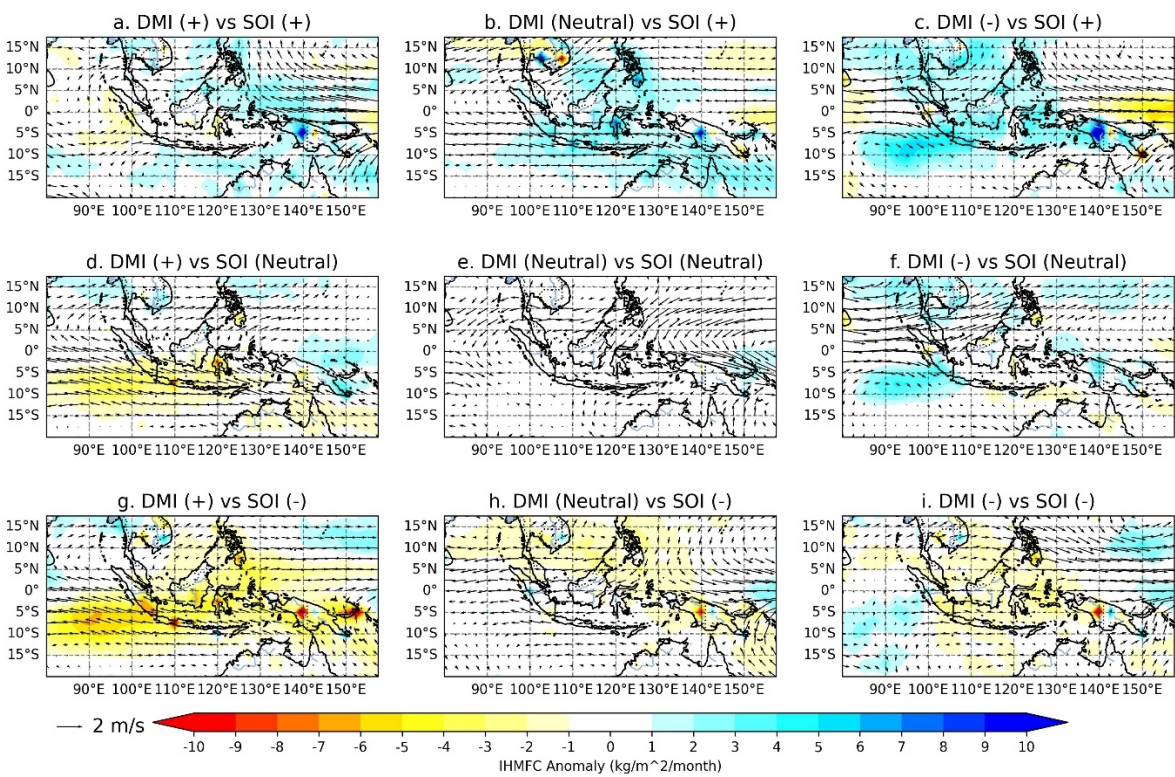


Figure 7. Same as Figure 4, but for monthly IHMFC anomalies and 850-hPa wind vector anomalies.

Table 1. The nine modes of ENSO and IOD phase combinations.

No.	Modes	DMI	SOI
1	DMI (+) vs SOI (+)	≥ 0.4	> 7
2	DMI (Neutral) vs SOI (+)	between -0.4 and 0.4	> 7
3	DMI (-) vs SOI (+)	≤ -0.4	> 7
4	DMI (+) vs SOI (Neutral)	≥ 0.4	between -7 and 7
	DMI (Neutral) vs SOI		
5	(Neutral)	between -0.4 and 0.4	between -7 and 7
6	DMI (-) vs SOI (Neutral)	≤ -0.4	between -7 and 7
7	DMI (+) vs SOI (-)	≥ 0.4	< -7
8	DMI (Neutral) vs SOI (-)	between -0.4 and 0.4	< -7
9	DMI (-) vs SOI (-)	≤ -0.4	< -7

Table 2. The number of months for each mode among the combinations of different ENSO and IOD phases from 1993 to 2022 (T DAYS dataset) and 1995 to 2014 (gridded FRD dataset).

Modes	DMI (+)		DMI (Neutral)		DMI (−)	
	1993/2022	1995/2014	1993/2022	1995/2014	1993/2022	1995/2014
SOI (+)	9	8	68	51	25	16
SOI	33	18	106	77	25	16
(Neutral)						
SOI (−)	34	14	50	33	10	7