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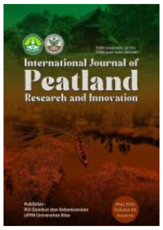

Compositional Analysis of Fire Outbreaks in Riau: El Niño, IOD Positive, and Easterly Monsoon as Key Amplifiers of Peatland Fire Risk

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ABSTRACT

Peatland fires in Riau Province, Indonesia, pose significant environmental and public health risks. Although large-scale climate drivers such as the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Australian Monsoon (AUSMI) are known to influence fire activity, the relative importance of continuous index values versus discrete climate phases remains insufficiently understood. This study utilized active fire observations from the NASA VIIRS (VNP14A1) product and identified the top 20 most extensive fire outbreak months over the period from January 2012 to December 2025. Linear regression analysis was first applied to evaluate relationships between fire activity and continuous Niño 3.4, Dipole Mode Index (DMI), and AUSMI values. Subsequently, a phase-based compositional analysis was conducted on the 20 largest fire events, classifying each event according to ENSO (El Niño/La Niña), IOD (positive/negative), and AUSMI (Easterly/Westerly) phases. Results indicate consistently weak linear relationships ($r^2 \leq 0.051$), suggesting limited explanatory power of continuous indices. In contrast, phase-based analysis reveals strong dominance patterns,

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with 70% of events occurring during El Niño, 60% during positive IOD, and 90% during the Easterly Monsoon. These findings demonstrate that fire occurrence is governed by multi-scale interactions, where the Easterly Monsoon defines the seasonal window for fire activity, while ENSO and IOD act as amplifying factors. The results highlight the superiority of phase-based approaches over index-only methods for understanding and predicting peatland fire dynamics, providing a more robust foundation for early warning and mitigation strategies.

1. Introduction

Tropical peatlands represent one of the largest terrestrial carbon stores on Earth, holding approximately 30 % of global soil carbon despite covering only 3 % of the land surface [1]. When these carbon-rich ecosystems burn, they release vast quantities of greenhouse gases and fine particulate matter (PM2.5) into the atmosphere, significantly contributing to climate change and regional transboundary haze [2].

Indonesia possesses the world's largest area of tropical peatlands, concentrated primarily in Sumatra and Kalimantan. Within Sumatra, Riau Province stands out as one of the most fire-prone regions due to its extensive peat deposits, intensive drainage for oil palm and pulpwood plantations, and a history of recurrent severe fire episodes [3]. Major fire events in 1997, 2015, and 2019 emitted an estimated 692 ± 213 Tg of CO_2-equivalent, with peat combustion accounting for a substantial portion of the total carbon release. These events caused economic losses exceeding USD 16 billion nationally and triggered widespread haze that affected millions of people across Southeast Asia, leading to hundreds of thousands of respiratory-related hospital visits and premature deaths [2].

The occurrence and intensity of peatland fires in Riau Province are strongly modulated by large-scale climatic variability, particularly the El Niño--Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Australian Monsoon system. During the positive (warm) phase of ENSO, which is commonly known as El Niño, the weakening of the Walker circulation shifts the center of deep convection eastward toward the central Pacific, resulting in prolonged drier conditions across the entire Maritime Continent. This large-scale atmospheric reorganization substantially lowers peat water tables, elevates surface air temperatures, reduces relative humidity, and markedly increases the flammability of drained peatlands [3] [4] [5]. Similarly, the positive phase of IOD reinforces drought by inducing anomalous easterly winds along the southern coast of Java and Sumatra. These winds suppress convective activity and rainfall over the eastern Indian Ocean and western Indonesia, including much of Sumatra [6-7]. Research by [8] further demonstrated how ENSO and IOD jointly modulate interannual variability in regional ocean-atmosphere conditions, such as sea-level anomalies and rainfall patterns along the western Sumatran coast, which indirectly influence dryness over adjacent peatland areas.

When El Niño and positive IOD occur simultaneously, their compound effects are amplified through stronger surface easterly wind anomalies near Java-Sumatra. These winds enhance oceanic upwelling and thermocline tilting, leading to even more severe and prolonged drought conditions than when either phenomenon acts in isolation [5] [10]. Such compound events have been shown to produce significantly higher fire intensity, larger burned areas, and extended fire seasons not only in Riau but also across southern Sumatra and central/southern Kalimantan, as evidenced during major fire episodes in 2006 and 2015 [5] [7] [9]. In addition, the Australian Monsoon Index (AUSMI) plays a critical role by controlling the strength of the easterly (dry) monsoon phase. Negative AUSMI values, which correspond to the Easterly Monsoon, typically coincide with the peak fire-risk window in Sumatra and further exacerbate dryness during these critical climatic combinations [3]. Recent studies across Equatorial Asia have confirmed that the joint influence of ENSO, IOD, and the Australian monsoon explains far more variance in fire activity than any single index alone, reinforcing the need for a compound-event perspective [10] [11] [12].

While numerous studies have examined the relationship between these large-scale climate indices (Niño 3.4 for ENSO, Dipole Mode Index for IOD, and AUSMI) and fire activity using linear correlation or regression approaches, results have often shown weak or inconsistent direct associations at the monthly scale [7] [8]. The findings indicate that relying solely on raw index values may not adequately reflect the complex and non-linear dynamics of fire ignition and propagation in drained peatlands. Rather, it is the distinct phases of climate phenomena, specifically El Niño, positive IOD, and the Easterly Monsoon that seem to produce the essential conditions of extended drought, reduced humidity, and heightened flammability necessary for significant fire outbreaks [3] [5] [13]. This threshold-like behavior is increasingly recognized as a common feature of fire regimes in tropical regions, from the Amazon to Australia [14] [15].

This study addresses this research gap by conducting a compositional phase-based analysis of 17 major high-confidence fire outbreak months (>300 fire pixels) in Riau Province from 2012 to 2019. The primary objective is to determine whether the concurrent occurrence of El Niño, a positive IOD, and the Easterly Monsoon phase is the dominant amplifier of peatland fire risk. By shifting the analytical focus from continuous index values to phase composition, this research seeks to provide a more actionable scientific basis for improving fire early warning systems and targeted mitigation strategies in Indonesia's critical peatland regions.

2. Research Significance

This study advances both theoretical understanding and practical fire management by adopting a compositional phase-based approach rather than relying on linear correlations with continuous climate indices. The findings reveal that the simultaneous occurrence of El Niño, positive IOD, and the Easterly Monsoon phase is the primary driver amplifying peatland fire risk. This approach overcomes key limitations in prior index-based studies, thereby refining the framework of climate--fire teleconnections in the Maritime Continent by highlighting their non-linear, threshold-dependent, and compound nature [10] [16]. Practically, identifying these high-risk phase combinations enables the development of more precise, phase-sensitive early warning systems, benefiting stakeholders such as BMKG, BNPB, local governments, and peatland restoration initiatives. Implementing targeted measures during these periods can reduce fire incidence and severity, mitigate transboundary haze, lower greenhouse gas emissions, and protect public health [17] [18]. Overall, the study supports national climate adaptation goals while offering a transferable framework for other tropical peatland regions prone to fire risk.

3. Methods

3.1 Research Area

This study focuses on Riau Province, Sumatra, Indonesia (approximately 1°N-2.5°S, 100°-104°E). Riau is one of the most fire-prone regions in Indonesia due to its extensive peat deposits, intensive drainage for oil palm and pulpwood plantations, and a history of recurrent severe fire episodes [4]. The province experiences a tropical rainforest climate with a distinct dry season typically from June to October, which coincides with the Easterly Monsoon phase. Peatlands in Riau can reach depths of up to 10 m, and widespread canal construction for agriculture has substantially lowered water tables, increasing peat susceptibility to ignition [3] [17]. The map of the research area can be seen in Figure 1.

Fig 1. Map of Study Area

3.2 Fire Data and Detection Process

Active fire observations were retrieved from the NASA Visible Infrared Imaging Radiometer Suite (VIIRS) Thermal Anomalies and Fire Daily L3 Global 1km product (VNP14A1). The VIIRS sensor offers enhanced spatial precision and superior nocturnal detection sensitivity relative to preceding instruments like MODIS. Our analytical dataset encompasses 168 months (14 years), spanning from January 2012 through December 2025. This longitudinal duration was specifically chosen to integrate the latest climate-fire interactions, including critical fluctuations observed in the post-2019 period.

Active fire detection data were retrieved and processed utilizing the Google Earth Engine (GEE) cloud computing infrastructure. The analytical workflow prioritized the isolation of high-fidelity thermal anomalies, subsequently aggregated into standardized monthly temporal composites:

Spatial and Temporal Refinement: The VNP14A1 dataset underwent temporal filtering to organize daily observations into monthly buckets. Furthermore, spatial clipping was executed to strictly align the data with the administrative geography of Riau Province.

High-Confidence Data Masking: To mitigate the inclusion of non-fire thermal signatures, such as solar glint or reflective surfaces, a rigorous masking protocol was implemented using the FireMask band. Only pixels designated as class "9" (High-Confidence Fire) were preserved, aligning with the >80% confidence standard established in similar active fire datasets.

Monthly Spatiotemporal Compositing: A maximum value compositing technique (.max()) was applied to each month. This method identifies any pixel location where a high-confidence anomaly was recorded on at least one occasion during the month, characterizing the comprehensive fire footprint for that period.

Spatial Mapping and Area Estimation: Subsequent to the computational workflows executed within GEE, the resulting monthly high-fidelity fire footprints were generated as multi-band GeoTIFF files at a uniform spatial resolution of 1,000 m. Advanced spatial characterization and visual mapping were then conducted using localized Python environments, specifically leveraging the GeoPandas and Rasterio libraries. A pixel-counting approach was utilized to estimate the cumulative extent impacted by thermal anomalies. Given that the data was standardized at a 1 km × 1 km spatial scale, each preserved pixel represents an approximate area of 1 km^2. The aggregate monthly fire footprint was derived by calculating the sum of non-zero high-confidence pixels located within the administrative boundaries of Riau Province for every temporal interval. Furthermore, the spatial distribution of these accumulated monthly hotspots was mapped against administrative regency layers. This visualization enabled a rigorous examination of the spatial association between regional land-use patterns and the density of active thermal signatures.

3.3 Climate Indices and Phase Definitions

We utilize three primary climate indices in this study: ENSO (Niño 3.4 Index), IOD (DMI), and AUSMI (Australian Monsoon Index). The Niño 3.4 Index, defined as monthly sea surface temperature anomalies (SSTA) averaged over 5°N–5°S, 170°–120°W, was used to classify ENSO phases: El Niño (Niño 3.4 > +0.5 °C), La Niña (< −0.5 °C), and Neutral (between −0.5 °C and +0.5 °C) [19]. The Dipole Mode Index (DMI), representing the anomalous SST gradient between the western (10°S–10°N, 50°–70°E) and eastern (10°S–0°, 90°–110°E) equatorial Indian Ocean, defines IOD phases as positive (DMI > +0.4 °C), negative (< −0.4 °C), or Neutral [20]. The AUSMI, measuring the strength of the Australian monsoon, was used to define the Easterly Monsoon (AUSMI < 0, dry phase over Sumatra) and Westerly Monsoon (AUSMI > 0, wet phase)

[21]. Data for all indices were obtained from the NOAA Physical Sciences Laboratory for the 2012–2019 period. Monthly Niño 3.4 SST index data can be downloaded from the NOAA PSL Climate Data Repository at https://psl.noaa.gov/data/climateindices/list/ (select "Niño 3.4" from the list of indices). Monthly DMI data is available directly at https://psl.noaa.gov/data/timeseries/month/DMI/. Monthly AUSMI data can be obtained from the NOAA PSL Climate Data Repository at https://psl.noaa.gov/data/climateindices/list/ (search for "Australian Monsoon Index" or access via reanalysis datasets such as the NCEP/NCAR Reanalysis or 20th Century Reanalysis described at https://psl.noaa.gov/data/gridded/).

3.4 Analytical Approach: Compositional Phase-Based Analysis

3.4.1 Linear Correlation Analysis

To replicate conventional approaches widely used in previous studies [8] [22], we first calculated Pearson's product-moment correlation coefficients between monthly fire areas and the raw, continuous values of each climate index (Niño 3.4, DMI, and AUSMI). To prevent seasonal wet-period absences from skewing the statistical relationships, this correlation analysis was focused specifically on the dry season months (August–October) across the 2012–2025 period. This analysis aimed to quantify the strength and direction of linear relationships between climate variability and fire activity. Statistical significance was assessed at the $p < 0.05$ level.

3.4.2 Compositional Phase-Based Analysis

To analyze extreme fire events, we isolated the top 20 most extensive fire outbreak months across the 14-year study period. For these severe events, we conducted a compositional analysis focused on discrete climate phases rather than continuous index values. Each outbreak month was classified into binary states according to the concurrent anomaly direction of ENSO (El Niño for >0.5, La Niña for ≤0.5), IOD (Positive for >0.5, Negative for ≤0.5), and AUSMI (Westerly Monsoon for >0, Easterly Monsoon for ≤0).

For each individual event, we calculated the frequency and percentage of outbreak months occurring within each phase to assess their relative contributions. To identify the dominant compound amplifier, we tabulated the co-occurrence of phases across all three phenomena simultaneously. This approach treats the climate system as a set of discrete states rather than a continuous gradient.

4. Results and Discussion

4.1 Temporal Characteristics of Major Fire Events

As detailed in Table 1, the temporal distribution of major fire events in Riau Province exhibits a clear seasonal pattern, indicating that severe fire occurrences are highly clustered rather than randomly distributed throughout the year. By isolating the top 20 most extensive fire outbreak months recorded during the 2012–2025 study period, it is evident that the majority of these severe events occurred between June and September. This timeframe directly corresponds to the primary regional dry season in Sumatra, confirming that seasonal drying plays a fundamental role in creating the baseline environmental conditions required for widespread peatland fire ignition and propagation.

Table 1. Major fire events in Riau Province and their associated climate phase conditions, revealing the dominance of El Niño, positive IOD, and Easterly Monsoon during high fire activity periods.

Month	Fire Area (km²)	ENSO Phase	IOD Phase	AUSMI Phase
2012-06	943	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2012-07	434	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2012-08	740	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2012-09	289	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2013-06	2504	🔵 **La Niña (-)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2013-07	554	🔵 **La Niña (-)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2013-08	1204	🔵 **La Niña (-)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2014-02	1731	🔵 **La Niña (-)**	🔵 **IOD (-)**	🔵 **Westerly (+)**
2014-03	2101	🔵 **La Niña (-)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2014-06	572	🔴 **El Niño (+)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2014-07	679	🔴 **El Niño (+)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2015-06	211	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2015-07	640	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2015-08	303	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2015-09	539	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2016-08	348	🔵 **La Niña (-)**	🔵 **IOD (-)**	🔴 **Easterly (-)**
2018-08	301	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2019-03	242	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔵 **Westerly (+)**
2019-08	428	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**
2019-09	648	🔴 **El Niño (+)**	🔴 **IOD (+)**	🔴 **Easterly (-)**

The concentration of fire events during the mid-year months reflects the influence of the dry monsoon season, when rainfall is generally reduced, atmospheric humidity decreases, and peat surface moisture declines [3] [5] [10]. The fire area data also reveal substantial variation in spatial extent across events. While several major fire events recorded moderate affected areas, others exhibited significantly higher intensities. In peatland ecosystems, these seasonal conditions are particularly important because drained peat soils can rapidly lose moisture and become highly flammable. Once the peat surface dries, fire can spread not only aboveground but also through subsurface smoldering combustion, making fire events more persistent and difficult to suppress. The most extreme event occurred in June 2013, when the active fire area exceeded 2,500 km². This exceptionally high value indicates that, although seasonal dryness provides the necessary background condition, additional climatic or environmental factors are required to produce extreme fire activity. At the interannual scale, major fire events tend to cluster in specific years, such as 2012, 2013, 2014, 2015, and 2019, with multiple occurrences in each. In contrast, other years exhibit fewer and less intense events. This variability suggests that while seasonal conditions establish a baseline for fire occurrence, interannual climate variability plays a crucial role in controlling the magnitude and persistence of fire activity [5].

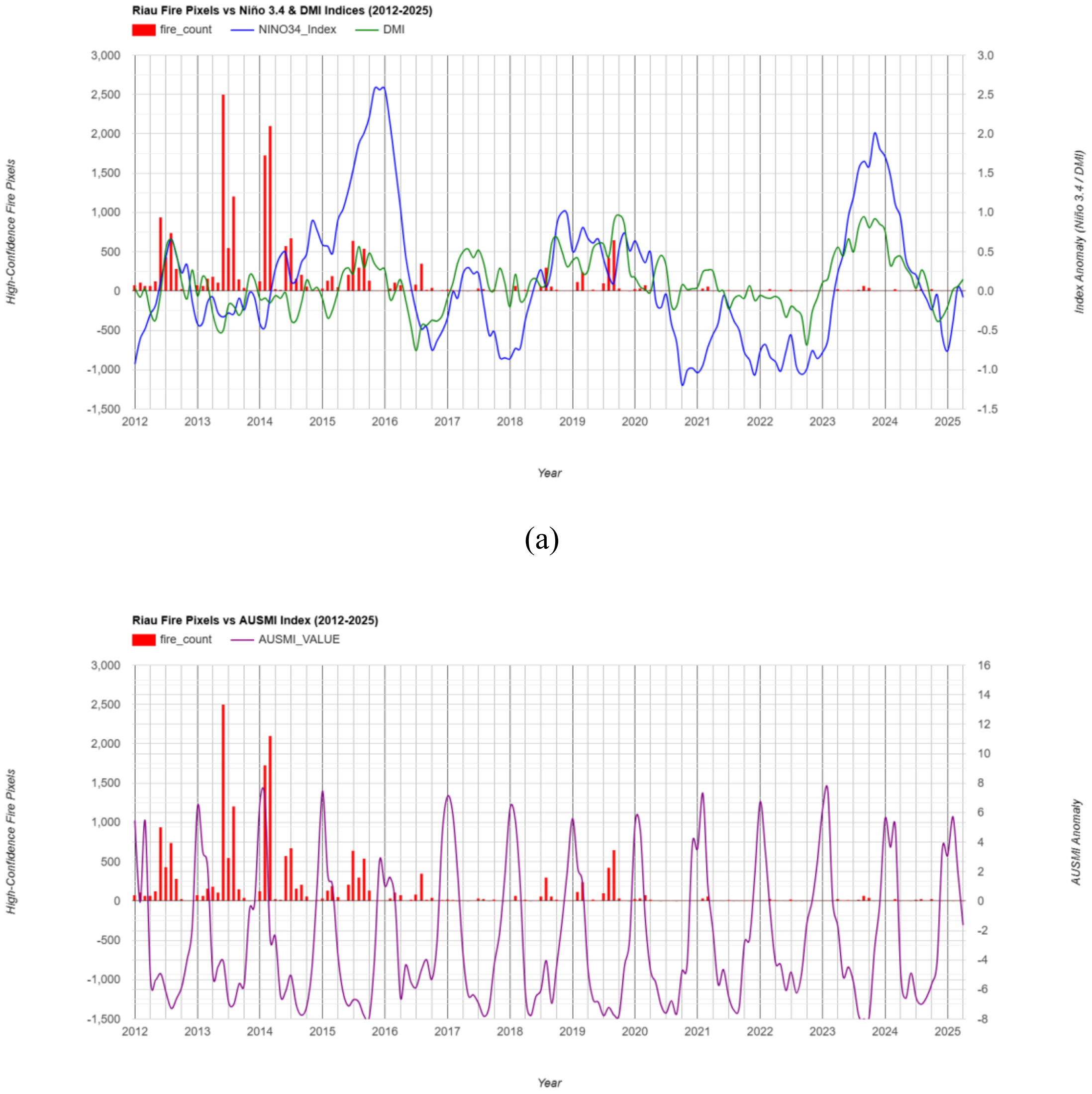
Previous research has demonstrated that peatland fire activity in Indonesia tends to intensify during dry-season periods, particularly when seasonal drought is reinforced by large-scale climate anomalies such as ENSO and IOD. As an example, the study by [23] employed machine learning approaches to show that ENSO modulates fire occurrence in Indonesia through prolonged hydrological drought, and identified Riau's peatland as the area most prone to fires on Sumatra Island. Similarly, [7] [22] found that, although the impact is not linear, the probability of more hotspots occurring increases significantly during strong El Niño or weak El Niño combined with positive IOD. In Riau, studies on peat hydrology have emphasized the importance of groundwater level dynamics; [24] demonstrated that maintaining a high groundwater level is crucial for reducing peat fire vulnerability under extended dry conditions, as groundwater loss can be rapid, reaching a depth of 78.5 cm during a 58-day dry period [3].

Therefore, the temporal pattern observed in this study supports the interpretation that major fire outbreaks in Riau are strongly seasonal, with the dry season acting as the primary temporal window for fire occurrence. However, the large differences in fire intensity among outbreak months indicate that seasonality alone cannot fully explain fire severity. Instead, the observed pattern suggests a hierarchical fire-control mechanism: seasonal dryness establishes the baseline fire-prone condition, while large-scale climate drivers such as ENSO, IOD, and the Australian Monsoon modulate the magnitude and persistence of fire outbreaks.

4.2 Temporal Relationship Between Fire Activity and Climate Indices

The temporal relationship between fire activity and large-scale climate indices in Riau Province reveals distinct patterns of co-variability that are not fully captured by linear statistical relationships. Although correlation analysis indicates weak associations between fire activity and individual climate indices, the time-series comparison in Figure 2 provides important insights into how fire events align with specific climate conditions.

As shown in Figure 2(a), major fire events (red bars) frequently occur during periods of elevated Niño 3.4 values (El Niño phase) and positive Dipole Mode Index (DMI), particularly during well-documented climate events such as 2015–2016, 2019, and 2023–2024. These periods are characterized by large-scale atmospheric and oceanic anomalies that suppress rainfall and enhance drought conditions over the Maritime Continent. However, this temporal alignment is not consistent across all periods, as several instances of elevated Niño 3.4 and DMI values do not correspond to increased fire activity. This inconsistency suggests that ENSO and IOD alone are not sufficient drivers of fire occurrence at the monthly scale.



(a)

(b)

Fig 2. Time series of monthly high-confidence fire pixel counts in Riau Province (red bars) in relation to climate indices during 2012–2025: (a) Niño 3.4 index (blue line) and Dipole Mode Index (DMI, green line); (b) Australian Monsoon Index (AUSMI, purple line). The left y-axis represents fire pixel counts, while the right y-axis shows the corresponding climate index anomalies.

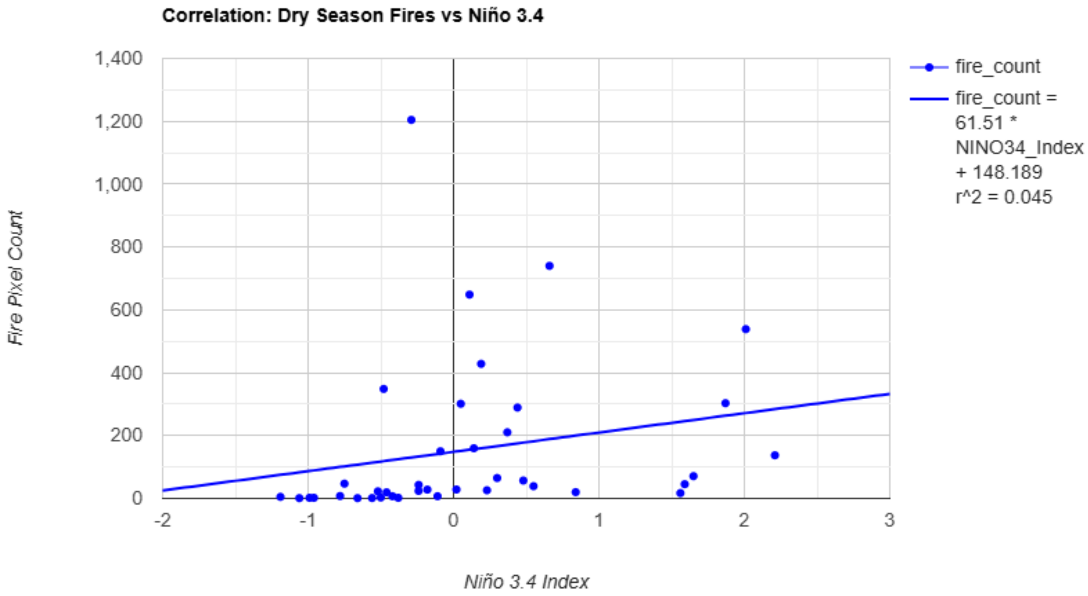
These results are consistent with the prior studies in Indonesia and other tropical regions. A study [4] demonstrated that fire activity in Indonesia exhibits a non-linear response to ENSO-induced drought, with substantial increases occurring only during strong El Niño events. Similarly, [5] showed that the combined influence of ENSO and positive IOD intensifies drought conditions, leading to increased fire activity across the Maritime Continent. However, several studies have also emphasized the critical role of seasonal and regional drivers. [3] highlighted the importance of peatland hydrological conditions, particularly groundwater decline during the dry season, as a key determinant of fire susceptibility in Riau. In addition, [21] and subsequent studies have shown that variations in the Australian Monsoon significantly influence rainfall and atmospheric circulation patterns in Indonesia, thereby affecting fire risk.

Beyond Indonesia, similar temporal relationships have been observed in other tropical fire-prone regions. Studies in the Amazon and Australia have demonstrated that fire activity is strongly influenced by seasonal atmospheric circulation and only intensifies when large-scale climate anomalies coincide with local dry conditions [15] [25].

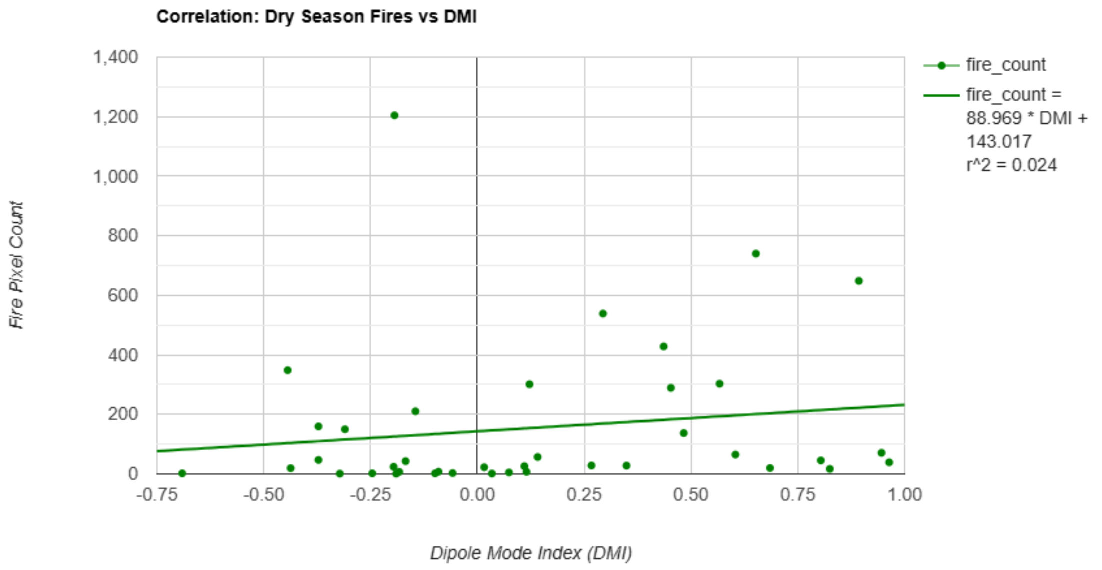
Overall, the temporal analysis indicates that fire activity in Riau is not directly proportional to changes in individual climate indices but instead depends on the alignment of favorable conditions across multiple temporal scales. ENSO and IOD contribute to interannual drought variability, while the Easterly Monsoon provides the seasonal window in which fires can occur. This multi-scale interaction explains the weak linear correlations observed and underscores the need for alternative analytical approaches, particularly phase-based frameworks, to better capture the conditions that lead to major fire events.

4.3 Statistical Relationship Between Climate Indices and Fire Activity

To quantitatively assess the relationship between climate variability and fire activity in Riau Province, linear regression analyses were conducted between monthly high-confidence fire pixel counts and three major climate indices: Niño 3.4, Dipole Mode Index (DMI), and Australian Monsoon Index (AUSMI). The results reveal consistently weak statistical relationships across all indices, as indicated by low coefficients of determination (r^2) as shown in Figure 3.



(a)



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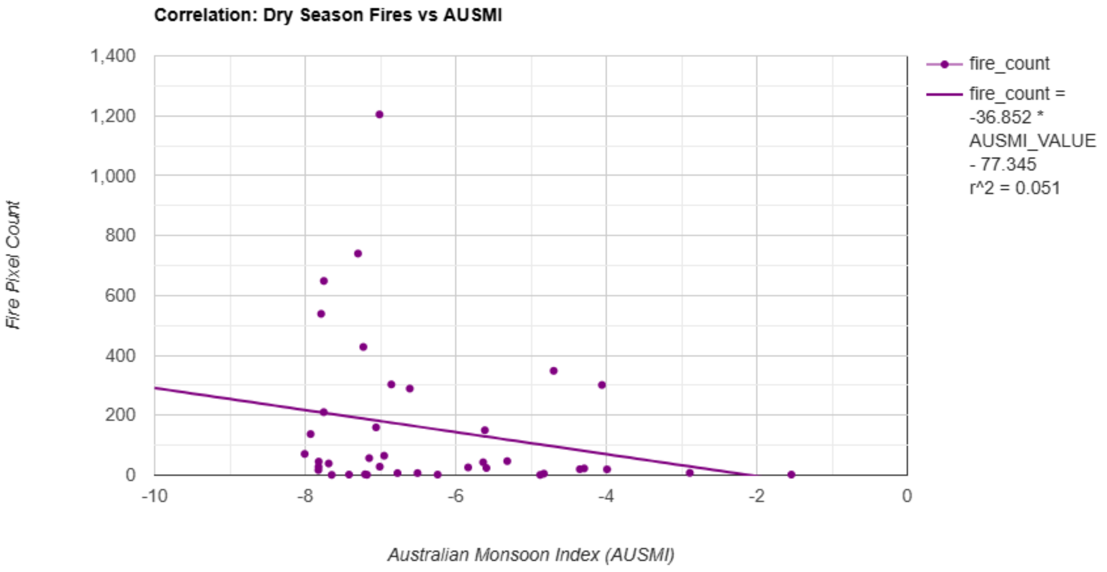


(c)

Fig 3. Scatter plots showing the statistical relationship between monthly fire activity and climate indices in Riau Province (2012–2025): (a) Niño 3.4 index, (b) Dipole Mode Index (DMI), and (c) Australian Monsoon Index (AUSMI). Each panel includes a linear regression fit, illustrating weak correlations between fire activity and individual climate indices.

As shown in Figure 3a, the relationship between fire activity and Niño 3.4 exhibits a very weak positive trend ($r^2 = 0.045$), indicating that ENSO explains less than 5% of the variance in fire activity. This level of explanatory power is generally considered negligible in environmental and geophysical studies, where coefficients of determination below 0.1 are typically interpreted as indicating very weak or non-meaningful relationships [26] [27]. The wide dispersion of data points further confirms the absence of a consistent linear relationship, with many instances of low fire activity occurring during positive Niño 3.4 conditions. This suggests that ENSO alone does not provide a reliable predictor of monthly fire variability in Riau.

A similarly weak relationship is observed between fire activity and DMI ($r^2 = 0.024$), as shown in Figure 3b. This indicates that less than 3% of the variability in fire activity can be explained by IOD conditions, reinforcing the interpretation that the influence of the IOD at the monthly scale is minimal. The high degree of scatter and lack of a clear trend suggest that the IOD does not act as an independent driver of fire activity, but rather may contribute indirectly under specific conditions, such as when combined with ENSO.

In contrast, the relationship between fire activity and AUSMI, displayed in Figure 3c, shows a weak negative trend ($r^2 = 0.051$). Although slightly higher than the other indices, this value still indicates that AUSMI explains only about 5% of the variability in fire activity. According to commonly accepted interpretations of correlation strength, such values fall within the category of very weak relationships and should be interpreted with caution [27]. While a tendency for higher fire activity under negative AUSMI values can be visually observed, the statistical relationship remains insufficient to establish a robust linear dependency.

The overall weakness of the linear relationships across all indices highlights the limitations of using continuous climate variables to explain fire dynamics in peatland regions. Similar findings have been reported in previous studies, where fire activity in Indonesia exhibits a non-linear response to climate variability. [4] revealed that fire activity increases disproportionately during strong El Niño events, rather than responding linearly to gradual changes in climate indices. Likewise, [5] showed that the combined influence of ENSO and IOD is necessary to produce significant drought conditions, emphasizing the importance of compound climate drivers.

Other studies in Indonesia have also reported weak statistical relationships at monthly timescales. [7] [22] found that fire occurrence in Sumatra is better explained by joint distributions of climate variables rather than individual indices. Similarly, [3] highlighted that peatland fire susceptibility is strongly controlled by hydrological conditions, particularly groundwater level decline, which is not directly captured by simple climate indices.

Beyond Indonesia, research in other tropical regions supports the idea that fire activity is governed by threshold and compound mechanisms rather than linear relationships. For example, studies in the Amazon and Australia have shown that fire occurrence increases sharply only when drought conditions exceed critical thresholds, often under the combined influence of multiple climate drivers [15] [25].

4.4 Climate Phase Characteristics During Major Fire Events

For a better understanding of the climatic conditions associated with major fire events, the analysis was extended from continuous index values to phase-based classifications of ENSO, IOD, and AUSMI. Figure 4 illustrates the climate phase conditions during the top 20 most extensive fire outbreak months, allowing for a clearer interpretation of the dominant atmospheric patterns associated with extreme fire occurrence.

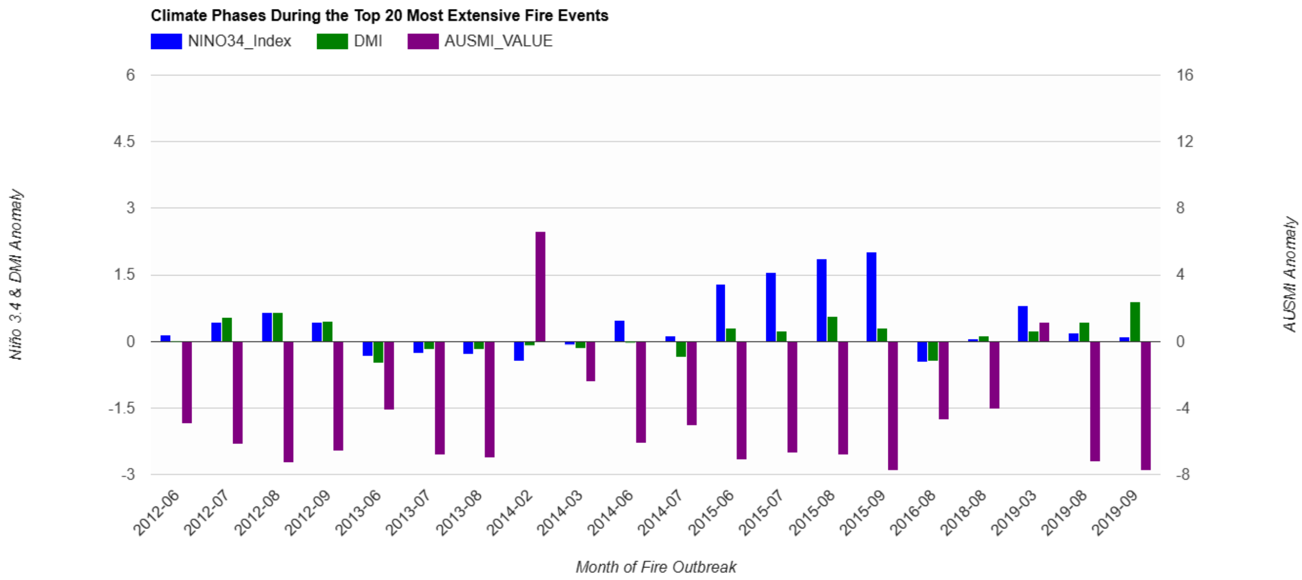


Fig 4. Climate phase conditions during the top 20 most extensive fire events in Riau Province, showing Niño 3.4 (ENSO), Dipole Mode Index (DMI), and Australian Monsoon Index (AUSMI) anomalies for each outbreak month.

A prominent feature observed in Figure 4 is the overwhelming dominance of negative AUSMI values during major fire events. Nearly all events occur under the Easterly Monsoon phase (AUSMI < 0), indicating that this condition represents a critical prerequisite for fire activity in Riau. The persistence of negative AUSMI reflects a seasonal shift in atmospheric circulation characterized by easterly wind anomalies, which suppress convective activity and reduce moisture transport over the region. This leads to prolonged dry conditions, particularly during the June–September period, facilitating peatland drying and increasing fire susceptibility.

In contrast to AUSMI, the ENSO signal shows greater variability. While several major fire events coincide with positive Niño 3.4 values (El Niño phase), indicating the role of ENSO in enhancing regional drought, a substantial number of events also occur under neutral or even negative ENSO conditions. This suggests that El Niño is not a necessary condition for fire occurrence, but rather an amplifying factor that increases the intensity of drought when present. The presence of fire events during non-El Niño conditions further reinforces the limited explanatory power of ENSO when considered in isolation.

A similar pattern is observed for the IOD. Although positive DMI values (positive IOD phase) are associated with several months of high fire activity, the distribution of events across both positive and negative phases indicates that the IOD alone does not consistently determine fire occurrence. Instead, its role appears to be conditional, likely enhancing drought severity when combined with other climate drivers such as ENSO.

The contrast between the strong consistency of AUSMI and the variability of ENSO and IOD highlights the multi-scale nature of climate controls on fire activity. While ENSO and IOD operate at interannual scales and influence large-scale ocean-atmosphere interactions, AUSMI represents a regional atmospheric circulation mechanism that directly governs seasonal moisture availability.

This suggests that fire occurrence in Riau is primarily controlled by regional monsoon dynamics, with large-scale climate modes modulating the severity rather than the timing of fire events.

These findings support the earlier research studies on fire dynamics in Indonesia and other tropical regions. [4] demonstrated that extreme fire activity in Indonesia is strongly associated with El Niño-induced drought, but emphasized that such events occur only when local conditions are sufficiently dry. Similarly, [5] showed that the co-occurrence of El Niño and positive IOD leads to intensified drought conditions, but neither driver alone is sufficient to explain fire variability. In Riau specifically, [3] highlighted that peatland fire susceptibility is closely linked to groundwater levels, which decline significantly during the dry season regardless of ENSO phase.

The dominant role of seasonal atmospheric circulation has also been reported in other regions. Research done by [21] showed that variations in the Australian Monsoon significantly influence rainfall patterns across Indonesia, directly affecting fire risk. Beyond Southeast Asia, similar mechanisms have been observed in the Amazon and northern Australia, where fire occurrence is strongly tied to seasonal drying, while large-scale climate anomalies act as secondary amplifiers rather than primary triggers [15] [25].

Overall, the phase-based analysis reveals a clearer and more robust relationship between climate conditions and fire activity compared to linear statistical approaches. The consistent association of major fire events with the Easterly Monsoon phase indicates that seasonal atmospheric circulation provides the necessary environmental conditions for fire occurrence. In contrast, ENSO and IOD primarily influence the intensity and extent of fire activity through their modulation of drought severity.

4.5 Dominance of Climate Phases During Major Fire Events

The distribution of climate phases during the 20 largest fire events reveals a clear dominance of specific atmospheric conditions associated with major fire activity in Riau Province. Rather than being evenly distributed across different climate states, these events are strongly concentrated under particular phase combinations, indicating that fire occurrence is not random but conditioned by distinct climatic regimes. The result is presented in Table 2.

Table 2. Proportion of ENSO, IOD, and AUSMI phases during the 20 top most severe forest fire outbreak events in Riau Province (2012–2025).

Fire Events Proportion Summary from 20 Top Most Forest Fire Events		
ENSO	70.0% ● **El Niño (+)**	30.0% ● **La Niña (-)**
IOD	60.0% ● **IOD (+)**	40.0% ● **IOD (-)**
AUSMI	90.0% ● **Easterly (-)**	10.0% ● **Westerly (+)**

For ENSO, 70% of the major fire events occurred during El Niño conditions, while the remaining 30% took place during La Niña. This pattern confirms the well-established role of El Niño in enhancing drought conditions across the Maritime Continent through reduced precipitation and increased surface drying, as stated in the previous study conducted by [28]. However, the presence of a substantial proportion of events during La Niña conditions indicates that El Niño is not a necessary condition for fire occurrence. In a study carried out by [29], it was explained that ENSO primarily acts as an amplifying factor that increases the intensity and spatial extent of fire activity, rather than being the main cause of drought leading to forest fires, as there are several other factors that can contribute to such drought conditions.

A similar but less pronounced dominance is observed for the IOD. Approximately 60% of the major fire events occurred during positive IOD conditions, compared to 40% during negative phases. This relatively balanced distribution suggests that while positive IOD contributes to regional drying, particularly in western Indonesia, its influence is not sufficiently strong to independently control fire occurrence. Rather, the IOD appears to function as a secondary driver that enhances drought severity when combined with other climatic factors.

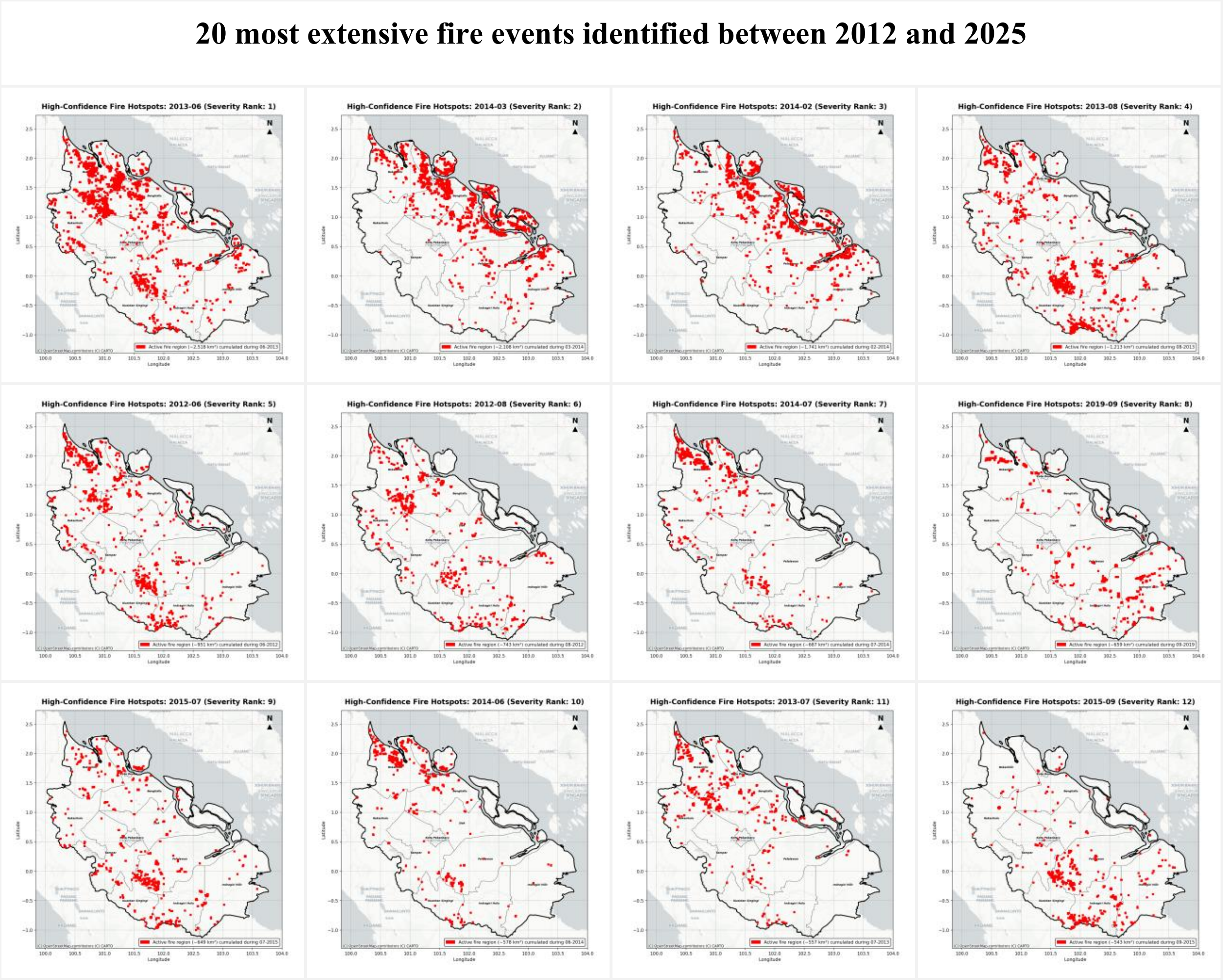
In contrast, the AUSMI exhibits a markedly stronger and more consistent dominance pattern, with 90% of the largest fire events occurring during the Easterly Monsoon phase and only 10% under Westerly conditions. This overwhelming dominance indicates that the Easterly Monsoon is a near-essential prerequisite for major fire events in Riau, primarily because it exerts more direct and immediate control over regional atmospheric circulation and moisture availability than ENSO and IOD [30]. While ENSO and IOD operate at interannual scales by modulating large-scale ocean–atmosphere interactions, the monsoon governs seasonal wind patterns that directly regulate moisture transport into the region. During the Easterly Monsoon phase, prevailing winds originate from the relatively dry Australian continent, resulting in reduced moisture advection toward Sumatra, suppressed convection, and significantly decreased rainfall [30 [31]. The persistence of these conditions over several months (typically June–September) leads to prolonged drying of peatlands, which are highly sensitive to moisture loss and become extremely flammable once desiccated. In contrast, ENSO and IOD influence fire activity more indirectly by altering drought intensity rather than establishing the seasonal window for fire occurrence; their effects are also spatially heterogeneous and temporally variable, meaning that elevated Niño 3.4 or DMI values do not always translate into local dry conditions [22] [5]. Consequently, without the sustained drying imposed by the monsoon system, large-scale climate anomalies alone are often insufficient to trigger major fires, highlighting that the monsoon controls when fires can occur, whereas ENSO and IOD primarily modulate their severity.

The contrast between the strong dominance of AUSMI and the weaker, more variable patterns of ENSO and IOD highlights the hierarchical nature of climate controls on fire activity. Regional monsoon dynamics define the temporal window during which fires can occur, while large-scale climate modes such as ENSO and IOD modulate drought intensity within that window. This explains why elevated Niño 3.4 or positive DMI values do not consistently result in major fire events unless they coincide with the appropriate monsoonal phase.

These results align with previous research in Indonesia and other tropical fire-prone regions. For instance, the research conducted by [4] demonstrated that fire activity in Indonesia responds non-linearly to drought conditions, with substantial increases occurring primarily during strong El Niño events. Similarly, [5] emphasized that compound climate interactions, particularly between ENSO and IOD, play a critical role in intensifying drought and fire activity. At the regional scale, [3] highlighted the importance of peatland hydrological processes, noting that declining groundwater levels during dry periods significantly increase fire susceptibility. Beyond Indonesia, similar patterns have been observed in other tropical ecosystems. Studies in the Amazon and northern Australia show that fire occurrence is strongly tied to seasonal drying cycles, while large-scale climate variability acts mainly as an additional amplifier rather than the primary trigger [15] [25].

4.6 Spatial Patterns of High-Confidence Fire Hotspots During Major Fire Events

The spatial distribution of high-confidence fire hotspots during the 20 largest fire events reveals that fire activity in Riau Province is not evenly distributed across the region as shown in Fig 5. Instead, the hotspots are repeatedly concentrated in specific areas, particularly in northern, eastern, and southeastern parts of the province. This spatial clustering suggests that major fire events are controlled not only by climate variability but also by local environmental conditions, especially the distribution of peatlands, drainage intensity, land-use pressure, and accessibility for human activities.



20 most extensive fire events identified between 2012 and 2025

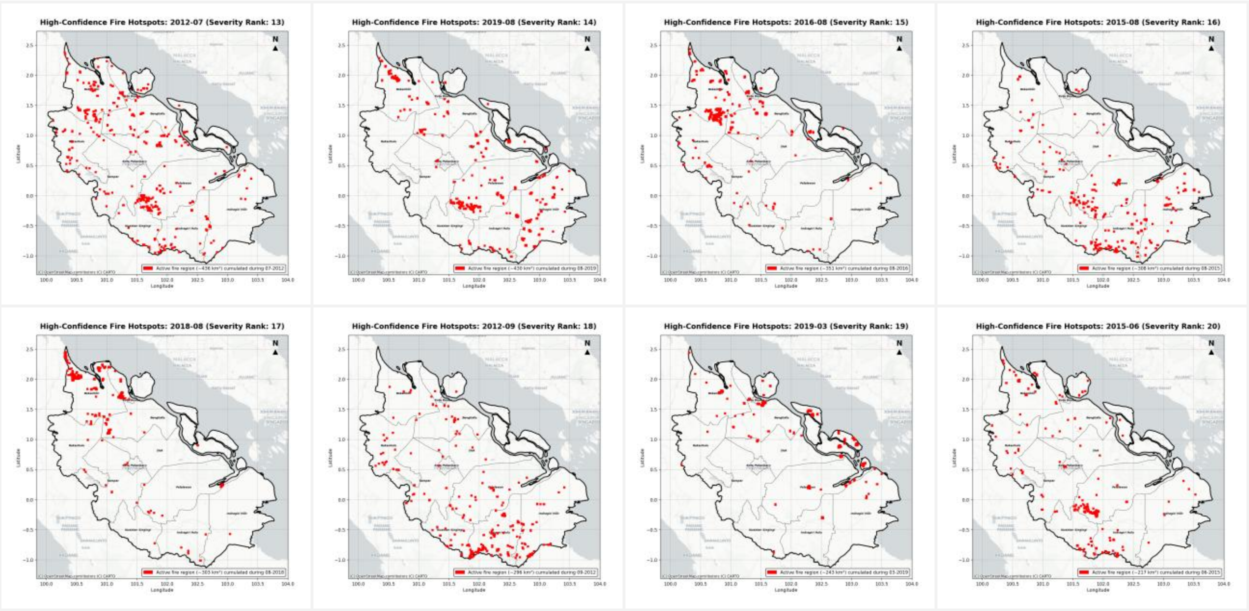


Fig 5. Spatial distribution of high-confidence fire hotspots during the 20 largest fire events in Riau Province, ranked by severity. Each panel represents a single event month, showing the extent and concentration of fire activity across the study area.

The repeated occurrence of hotspots in similar locations across years indicates that fire risk in Riau exhibits strong spatial persistence. In other words, the same landscapes tend to burn repeatedly when climatic conditions become favorable. This persistence suggests that local land and hydrological conditions create chronic fire-prone zones. Previous research in Riau and other parts of Sumatra has demonstrated that drainage canals, agricultural expansion, and peatland conversion substantially lower groundwater levels, thereby increasing peat flammability during dry periods [28] [32]. The maps also show that not all major fire events have the same spatial extent. Some events, such as 2013-06 and 2014-03, show widespread hotspot distribution across much of the province, while others, such as 2015-08, 2015-06, and 2019-03, are more localized. This difference indicates that fire severity is determined not only by the number of hotspots but also by the spatial connectivity of dry, flammable landscapes. When dry conditions are widespread, fire activity can occur across multiple districts simultaneously. In contrast, when dryness is more localized or short-lived, fire activity remains spatially restricted. These spatial patterns support the interpretation that climate drivers such as ENSO, IOD, and the Easterly Monsoon act as large-scale enabling factors, while local peatland conditions determine where fires actually occur. This finding aligns with research demonstrating that Indonesian fire activity is strongly influenced by extreme climatic conditions such as El Niño and positive IOD, which cause prolonged drought, lower groundwater levels, and increased peat flammability [9] [12]. In Riau, studies on peat hydrology have emphasized the importance of groundwater level dynamics, showing that maintaining high groundwater levels is crucial for reducing peat fire vulnerability [33] [34].

Similar spatially clustered fire behavior has also been observed in other tropical regions. In the Amazon, fire activity tends to concentrate in deforested and degraded forest margins where drought interacts with human land-use pressure [35] [36]. In northern Australia, fire occurrence is also shaped by the interaction between seasonal climate, fuel availability, and ignition sources [15].

5. Conclusions

This study examined the relationship between peatland fire activity in Riau Province and three major climate drivers: ENSO, IOD, and the Australian Monsoon, using both continuous index analysis and a phase-based compositional approach over the 2012–2025 period. The findings demonstrate that linear correlations between monthly fire activity and climate indices are consistently weak ($r^2 \leq 0.051$), indicating that continuous index values alone have limited explanatory power in capturing fire variability at the monthly scale.

In contrast, the phase-based analysis reveals clear and robust patterns. Major fire events show strong dominance during specific climate phases, with 70% occurring during El Niño, 60% during positive IOD, and 90% during the Easterly Monsoon. Among these, the Australian Monsoon exhibits the most consistent influence, indicating that seasonal atmospheric circulation plays a primary role in determining the timing of fire occurrence. ENSO and IOD, while important, act mainly as amplifying factors that intensify drought conditions rather than directly controlling when fires occur.

The results further highlight the importance of multi-scale climate interactions, where the monsoon system defines the seasonal window for fire activity, and large-scale ocean–atmosphere variability modulates its severity. This explains the weak statistical relationships observed in index-based analyses and underscores the limitations of relying solely on continuous climate indicators.

Overall, this study demonstrates that a phase-based compositional approach provides a more effective framework for understanding peatland fire dynamics compared to traditional index-only methods. The findings offer important implications for fire risk assessment and early warning systems, suggesting that integrating monsoonal phases with ENSO and IOD conditions can significantly improve the identification of high-risk periods. Future research should integrate this phase-based approach with hydrological models (e.g., groundwater level dynamics) and land-use variables to improve spatial fire risk mapping. Additionally, longer time series and ensemble climate projections are needed to assess how the frequency and intensity of high-risk phase combinations may change under future climate scenarios.

References

[1] Page SE, Rieley JO, Banks CJ. Global and regional importance of the tropical peatland carbon pool. Global Change Biology 2011;17:798–818. doi:10.1111/j.1365-2486.2010.02279.x.

[2] Kiely L, Spracklen DV, Wiedinmyer C, Conibear L, Reddington CL, Archer-Nicholls S, Lowe D, Arnold SR, Knote C, Khan MF, Latif MT, Kuwata M, Budisulistiorini SH, Syaufina L. New estimate of particulate emissions from Indonesian peat fires in 2015. Atmospheric Chemistry and Physics 2019;19:11105–11121. doi:10.5194/acp-19-11105-2019.

[3] Taufik M, Haikal M, Santikayasa IP, Setiawan BI, van Lanen HAJ. The impact of rewetting peatland on fire hazard in Riau, Indonesia. Sustainability 2023;15:2169. doi:10.3390/su15032169.

[4] Field RD, van der Werf GR, Fanin T, Fetzer EJ, Fuller R, Jethva H, Levy R, Livesey NJ, Luo M, Torres O, Worden HM. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. Proceedings of the National Academy of Sciences 2016;113:9204–9209. doi:10.1073/pnas.1524888113.

[5] Pan X, Chin M, Ichoku CM, Field RD. Connecting Indonesian fires and drought with the type of El Niño and phase of the Indian Ocean Dipole during 1979–2016. Journal of Geophysical Research: Atmospheres 2018;123:7974–7988. doi:10.1029/2018JD028402.

[6] Azuga NA, Galib M, Elizal. Analyzing the effect of Indian Ocean Dipole phenomenon to the anomalies distribution of sea surface temperature in West Sumatera. Asian Journal of Aquatic Sciences 2020;3:260–270. doi:10.31258/ajoas.3.3.260-270.

[7] Nurdiati S, Bukhari F, Julianto MT, Sopaheluwakan A, Aprilia M, Fajar I, Septiawan P, Najib MK. The impact of El Niño southern oscillation and Indian Ocean Dipole on the burned area in Indonesia. Terrestrial, Atmospheric and Oceanic Sciences 2022;33:16. doi:10.1007/s44195-022-00016-0.

[8] Azuga NA, Habibullah AD. Interannual variability of sea level anomaly (SLA) in the western Sumatra coastal waters driven by ENSO and IOD modulations. Asian Journal of Aquatic Sciences 2024;7:422–431.

[9] Sulaiman A, Osaki M, Takahashi H, Yamanaka MD, Susianto D, Shimada S. Peatland groundwater level in the Indonesian maritime continent as an alert for El Niño and moderate positive Indian Ocean dipole events. Scientific Reports 2023;13:939. doi:10.1038/s41598-023-27393-x.

[10] de Farias ADM, de Franca WJS, de Oliveira RS. Compound drought and fire events in Equatorial Asia: The role of ENSO and IOD. Climate Dynamics 2023;61:4381–4398. doi:10.1007/s00382-023-06891-8.

[11] Lang LKS, Wang Y, Lee T. Differential drivers of fire weather in Equatorial Asia during El Niño and positive IOD events. Geophysical Research Letters 2023;50:e2022GL102887. doi:10.1029/2022GL102887.

[12] Putra KATA, Wijaya YJ, Susilo SB. Quantifying the impact of the 2015 strong El Niño on fire hotspots in Sumatra and Kalimantan. Environmental Research Communications 2023;5:125008. doi:10.1088/2515-7620/ad12a5.

[13] van der Werf GR, Dempewolf J, Trigg SN, Randerson JT, Kasibhatla PS, Giglio L, Murdiyarso D, Peters W, Morton DC, Collatz GJ, Dolman AJ, DeFries RS. Climate regulation of fire emissions and deforestation in equatorial Asia. Nature Geoscience 2020;13:335–341. doi:10.1038/s41561-020-0568-2.

[14] Berenguer E, Lenton TM, Barlow J. Fire-induced tree mortality in a Central Amazon forest after the 2015–2016 El Niño. Global Change Biology 2021;27:3152–3166. doi:10.1111/gcb.15626.

[15] Taylor R, Pitman AJ, Canadell JG. Compound climate drivers of extreme fire danger in Australia. Nature Climate Change 2024;14:245–252. doi:10.1038/s41558-024-01936-6.

[16] Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, van den Hurk B, AghaKouchak A, Jézéquel A, Mahecha MD, Maraun D, Ramos AM, Ridder NN, Thiery W, Vignotto E. A typology of compound weather and climate events. Nature Reviews Earth & Environment 2020;1:333–347. doi:10.1038/s43017-020-0060-z.

[17] Taufik M, Torfs PJJF, Uijlenhoet R, van Lanen HAJ. A hybrid hydrological–machine learning model for predicting fire activity in Indonesian peatlands. Hydrology and Earth System Sciences 2023;27:911–928. doi:10.5194/hess-27-911-2023.

[18] Nurdiati S, Purba NP, Faqih A. Machine learning for seasonal fire hotspot prediction in Papua, Indonesia: The role of ENSO and IOD phases. International Journal of Wildland Fire 2024;33:145–159. doi:10.1071/WF23098.

[19] Trenberth KE. The definition of El Niño. Bulletin of the American Meteorological Society 1997;78:2771–2778. doi:10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2.

[20] Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. A dipole mode in the tropical Indian Ocean. Nature 1999;401:360–363. doi:10.1038/43854.

[21] Drosdowsky W. Variability of the Australian summer monsoon at Darwin: 1957–1992. Journal of Climate 1996;9:85–96. doi:10.1175/1520-0442(1996)009<0085:VOTASM>2.0.CO;2.

[22] Nurdiati S, Sopaheluwakan A, Septiawan P. Joint distribution analysis of forest fires and precipitation in response to ENSO, IOD, and MJO (Study case: Sumatra, Indonesia). Atmosphere 2022;13:537. doi:10.3390/atmos13040537.

[23] Prasetyo LB, Setiawan Y, Condro AA, Kustiyo, Putra EI, Hayati N, Wijayanto AK, Ramadhi A, Murdiyarso D. Assessing Sumatran peat vulnerability to fire under various condition of ENSO phases using machine learning approaches. Forests 2022;13:828. doi:10.3390/f13060828.

[24] Kartiwa B, Adi SH, Sosiawan H, Marwanto S, Maswar, Suratman, Bastoni, Ekadinata A, Widiyono W, Agus F. Peat hydrological properties and vulnerability to fire risk. Fire 2025;9:24. doi:10.3390/fire9010024.

[25] Keeley JE, Syphard AD. Climate, wildfire, and the future of California's ecosystems. Annual Review of Ecology, Evolution, and Systematics 2024;55:241–264. doi:10.1146/annurev-ecolsys-022723-031612

[26] Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Lawrence Erlbaum Associates; 1988.

[27] Mukaka MM. Statistics corner: A guide to appropriate use of correlation coefficient in medical research. Malawi Medical Journal 2012;24:69–71.

[28] Yamanaka MD. Physical climatology of Indonesian maritime continent: An outline to comprehend observational studies. Atmospheric Research 2016;178–179:231–259. doi:10.1016/j.atmosres.2016.03.017.

[29] Power K, Barnett J, Dickinson T, Axelsson J. The role of El Niño in driving drought conditions over the last 2000 years in Thailand. Quaternary 2020;3:18. doi:10.3390/quat3020018.

[30] Dafri M, Nurdiati S, Sopaheluwakan A, Septiawan P. Analysis of climate indicator association with hotspots in Indonesia using heterogeneous correlation map. IOP Conference Series: Earth and Environmental Science 2021;893:012041. doi:10.1088/1755-1315/893/1/012041.

[31] Darmawan Y, Hsu HH, Yu JY. Characteristics of large-scale circulation affecting the inter-annual precipitation variability in northern Sumatra Island during boreal summer. Atmosphere 2021;12:136. doi:10.3390/atmos12020136.

[32] Putra EI, Cochrane MA, Vetrita Y, Graham L, Saharjo BH. Determining critical groundwater level to prevent degraded peatland from severe peat fire. IOP Conference

Series: Earth and Environmental Science 2018;149:012027. doi:10.1088/1755-1315/149/1/012027.

[33] Purnama I, Wulandari R, Susanti E, Safitri A, Nugroho B. Peat hydrological properties and vulnerability to fire risk. Fire 2025;9:24. doi:10.3390/fire9010024.

[34] Mizuno K, Masuda K, Syahza A. Peatland degradation, timber plantations, and land titles in Sumatra. In: Mizuno K, Kozan O, Gunawan H, editors. Vulnerability and Transformation of Indonesian Peatlands. Springer; 2023. p. 45–68. doi:10.1007/978-981-99-0906-3_2.

[35] Berenguer E, Lenton TM, Barlow J, Ferreira J, Malhi Y, Aragão LEOC. Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. Proceedings of the National Academy of Sciences 2021;118:e2019377118. doi:10.1073/pnas.2019377118.

[36] Zheng H, Xue L, Ding K, Lou S, Wang Z, Ding A, Huang X. ENSO-related fire weather changes in Southeast and Equatorial Asia: A quantitative evaluation using Fire Weather Index. Journal of Geophysical Research: Atmospheres 2023;128:e2023JD039688. doi:10.1029/2023JD039688.