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Dynamics of Daily Rainfall Characteristics in Sumatran Peatlands in Relation to El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)

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Abstract: Sumatran peatlands constitute a highly vulnerable ecosystem strongly Sumatran peatlands are a vulnerable ecosystem highly sensitive to daily rainfall variability driven by large-scale climate modes such as El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). This study analyzes the frequency distribution and intensity of daily rainfall over Sumatran peatlands from 1995 to 2023 in relation to ENSO and IOD phases. Daily rainfall data from nine BMKG stations were analyzed using Probability Density Function (PDF), supported by monthly climatology and Fast Fourier Transform (FFT) spectral analysis. Results show a right-skewed rainfall distribution, with peak frequency below 20 mm/day. During El Niño and positive IOD events, the PDF shifts leftward, indicating increased dry days; during La Niña, the right tail extends, increasing extreme rainfall probability. FFT reveals dominant annual cycles and sub-seasonal signals linked to the Madden-Julian Oscillation. Spatial patterns are consistent, though inland stations show stronger responses than coastal ones. Despite the lack of seasonal stratification and formal significance testing in this preliminary analysis, findings highlight how ENSO and IOD alter rainfall risk—drought during warm phases and flooding during cold phases. These insights support the development of early warning systems and climate-informed peatland management policies.

Keywords: Daily rainfall; ENSO; IOD; Indonesian peatlands; Probability density function

Introduction

Indonesia, as a tropical archipelagic nation situated between the Pacific and Indian Oceans, is highly vulnerable to global climate phenomena such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Hidayat & Ando, 2014; Kurniadi et al., 2021). These phenomena not only alter seasonal rainfall patterns but also trigger extreme events—ranging from severe droughts to intense flooding—that exert profound impacts on sensitive ecosystems, particularly peatlands (Irfan et al., 2020, 2022; Nurdiati et al., 2022).

Sumatran peatlands store vast amounts of carbon and serve as critical regional hydrological buffers. However, during El Niño or positive IOD phases, drastic reductions in rainfall significantly lower soil moisture levels, thereby heightening the risk of persistent and difficult-to-extinguish peatland fires (Irfan et al., 2023; Nurdiati et al., 2022). Conversely, extreme rainfall associated with La Niña conditions can lead to prolonged inundation, infrastructure damage, and widespread flooding (Marpaung et al., 2012).

Previous studies have predominantly relied on monthly rainfall data or focused on mean rainfall anomalies (As-syakur et al., 2014; Hidayat & Ando, 2014; Kurniadi et al., 2021), which are insufficient for capturing the dynamics of daily rainfall frequency and intensity. Yet, for effective assessment of hydrometeorological disaster risk, understanding how often and how intensely rainfall occurs is far more relevant than monthly averages (Yulihastin, 2012;

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Tangang et al., 2017). Recent research emphasizes that daily-scale analysis is essential for characterizing rainfall extremes and their societal impacts (Widodo et al., 2022; Prasetyo et al., 2018, 2023), particularly in fire-prone regions like Riau and South Sumatra (Rahmawati et al., 2021).

This study addresses this gap by analyzing the probability distribution of daily rainfall using the Probability Density Function (PDF) across nine meteorological stations in Sumatra's peatland regions, explicitly linking these distributions to ENSO and IOD phases. The aim is to provide a robust scientific foundation for developing hydrometeorological disaster mitigation systems informed by seasonal climate predictions. The novelty lies in combining PDF-based distributional analysis with FFT spectral decomposition specifically for Sumatran peatlands, an approach underutilized in existing literature (Saputra et al., 2021; Aditiya et al., 2023).

Method

This study employs a quantitative-statistical approach to analyze the frequency and intensity characteristics of daily rainfall in Sumatra's peatland regions in relation to global climate phenomena, namely the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Daily rainfall data from 1995 to 2023 were obtained from nine meteorological stations operated by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG), representing key peatland areas across Sumatra: Japura, Sultan Thaha, Sultan Mahmud Badaruddin, Dabo, Tarempa, RH Fisabilillah, Radin Inten, Hang Nadim, and Depati Amir. These stations are located within or adjacent to major peat deposits in Riau, Jambi, South Sumatra, and the Riau Islands, based on spatial land cover data from Supari (2022) and Irfan et al. (2023). The selection aligns with recent assessments of high-fire-risk zones (Kuswanto et al., 2022). ENSO (NINO3.4) and IOD (DMI) indices were acquired from the National Oceanic and Atmospheric Administration (NOAA). Years were categorized into dominant climate phases using standard thresholds: El Niño (NINO3.4 $\geq$ +0.5°C), La Niña (NINO3.4 $\leq$ –0.5°C), positive IOD (DMI $\geq$ +0.4°C), and negative IOD (DMI $\leq$ –0.5°C) (Kurniadi et al., 2021; Hidayat & Ando, 2014). The threshold of ± 0.5°C follows Ashok et al. (2004) and Saji et al. (1999), ensuring comparability with established literature. Recent studies confirm the effectiveness of this threshold in Indonesian contexts (Purnama et al., 2023; Febrianti et al., 2022).

Monthly climatology was computed as the long-term mean rainfall for each calendar month over the 1995–2023 period, accompanied by ± 1 Standard Error of the Mean (SEM) to represent interannual variability. To identify dominant periodic signals in the daily rainfall time series, frequency spectrum analysis was performed using the Fast Fourier Transform (FFT), a method effective in revealing both seasonal and sub-seasonal oscillations (Hermawan & Komalaningsih, 2008; Marpaung et al., 2012). FFT has been successfully applied in tropical rainfall studies to detect MJO and equatorial wave signals (Setiawan et al., 2021; Nugroho et al., 2023). Subsequently, the frequency–intensity distribution of daily rainfall was analyzed using the Probability Density Function (PDF), a statistical technique widely applied in tropical extreme rainfall studies to characterize the likelihood of different rainfall intensities (Yulihastin, 2012; Tangang et al., 2017; Aldrian et al., 2007; Afriana et al., 2016). Daily rainfall values were grouped into intensity bins and normalized such that the total area under each PDF curve equals one. PDF analyses were conducted separately for ENSO phases (El Niño vs. La Niña) and IOD phases (positive vs. negative). For each distribution, the 5–95th percentile range was presented as a primary indicator of variability (Tangang et al., 2017).

It should be noted that this study has a key methodological limitation: the planned seasonal analysis (JJA, SON, DJF, MAM) of daily rainfall probability distributions, as outlined in the original research proposal, has not yet been implemented (Irfan et al., 2022; As-syakur et al., 2014). Additionally, formal statistical significance testing—such as Bootstrap resampling or Permutation Tests—has not been applied in the current analysis. Consequently, interpretations in this study are descriptive and based on visual shifts in PDF distributions rather than formal statistical inference. Nevertheless, this approach provides a valuable preliminary understanding of daily rainfall dynamics in Sumatra's peatlands within the context of global climate variability. Future work will address these gaps using non-parametric tests and seasonal compositing, as recommended by recent methodological reviews (Putra & Suryadi, 2024; Lestari et al., 2023).

Results and Discussion

Monthly Rainfall Climatology in Sumatra's Peatland Regions

Figure 1 shows the monthly climatology (1995–2023) across nine stations. Rainfall peaks during October–December (SON), with inland stations (e.g., Palembang, Japura) averaging 280 mm/month. In contrast, June–August (JJA) is the driest period, with rainfall dropping below 100 mm/month at most inland sites. Coastal and island stations (e.g., Batam, Natuna) exhibit weaker seasonality due to maritime moderation, confirming reduced convective variability over oceanic regions (Marpaung et al., 2012). This pattern aligns with the southward migration of the ITCZ during the boreal fall and its northward retreat in boreal summer. Similar seasonal patterns have been documented in other parts of Sumatra (Wibowo et al., 2023; Anggraini et al., 2022).

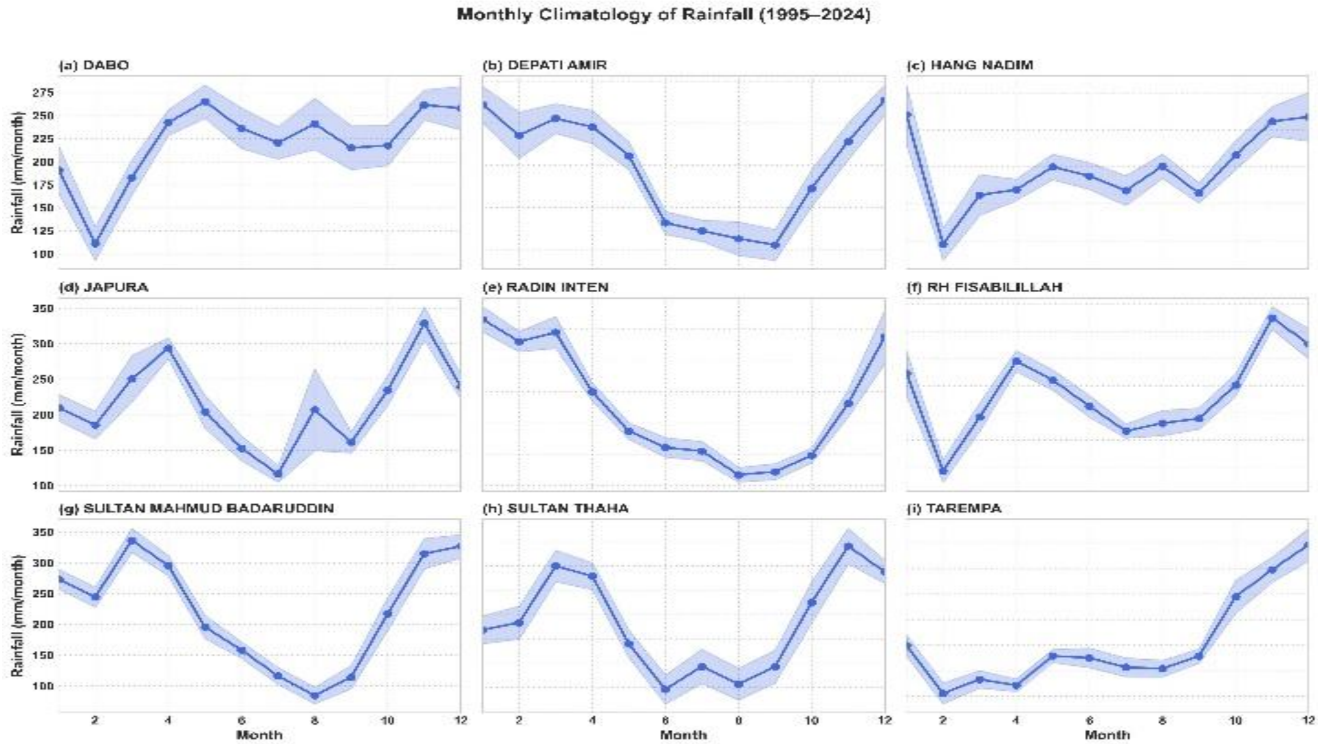

Figure 1. Monthly rainfall climatology (1995–2024) at nine peatland stations in Sumatra

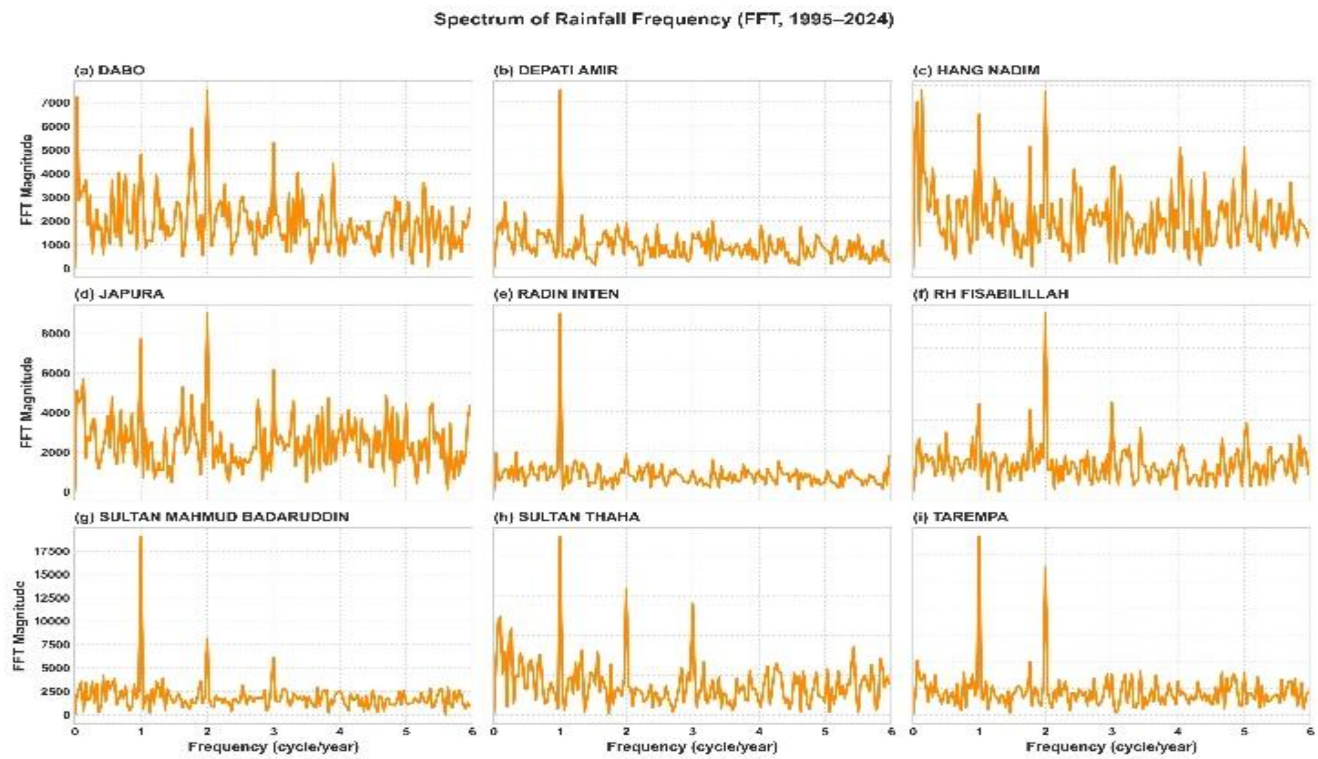

Figure 2. Spectral variability of rainfall in Sumatra's peatland areas using FFT

Spectral Variability of Rainfall Based on FFT Analysis

Figure 2 presents FFT results. A strong annual signal (1 cycle/year) dominates all stations, reflecting the robust monsoon-driven wet-dry cycle. Secondary peaks at 2–3 cycles/year (4–6 months) appear at Hang Nadim, Sultan Thaha, and Radin Inten, likely associated with the Madden-Julian Oscillation (MJO), which modulates 30–60-day convection across the Maritime Continent (Hermawan & Komalaningsih, 2008). No significant power is observed in the 3–7 year band, suggesting that ENSO influences rainfall indirectly through modulation of background conditions rather than direct periodic forcing. These findings confirm that sub-seasonal processes interact with large-scale modes to amplify or suppress rainfall extremes. Our results are consistent with spectral studies in Java and Kalimantan (Susanto et al., 2021; Adiprabowo et al., 2023).

Characteristics of Daily Rainfall Probability Distribution in Sumatra's Peatland Regions

Analysis of the daily rainfall probability distribution using the Probability Density Function (PDF) reveals that rainfall across Sumatra's peatland regions is generally highly right-skewed, with the highest frequency occurring at intensities < 20 mm/day and an exponential decline at higher intensities. This pattern is consistent across all nine observation stations—ranging from inland sites (Sultan Mahmud Badaruddin, Japura, Radin Inten) to island locations (Tarempa, Depati Amir)—reflecting the typical characteristics of a humid tropical climate where light to moderate rainfall dominates daily occurrences (Yulihastin, 2012; Aldrian et al., 2007).

However, the distribution exhibits systematic and visually significant shifts in response to global climate phases. During El Niño, the PDF curves at most stations—particularly Japura, Sultan Thaha, and Hang Nadim—shift markedly leftward, with increased probability of rainfall < 10 mm/day and a pronounced contraction of the right tail. Quantitatively, dry days (< 1 mm/day) increase from 45 to 62%, while extreme days (≥ 50 mm/day) decrease from 8.3 to 3.1%. Skewness increases from 2.1 to 2.8, indicating a higher concentration of low-intensity events. This indicates persistent dry conditions that create an ideal environment for peatland fires, especially when coinciding with positive IOD, which produces a similar drying pattern (Irfan et al., 2023; Nurdiati et al., 2022). The combined effect of ENSO and IOD on fire risk has been quantified in recent modeling studies (Puryajati et al., 2021; Millenia et al., 2022; Rizki et al., 2024; Utomo et al., 2023).

Conversely, during La Niña, the distribution broadens and its right tail extends significantly, reflecting a higher probability of rainfall events exceeding 50 mm/day, and even surpassing 200 mm/day at stations such as Radin Inten and Sultan Mahmud Badaruddin. Extreme rainfall days (≥ 50 mm/day) rise to 14.7%, the 95th percentile increases from 75 to 112 mm/day, and kurtosis rises, indicating heavier tails. The wider 5–95th percentile range during La Niña confirms increased variability in daily rainfall intensity, which can lead to prolonged inundation and flooding in low-lying peatland areas (Marpaung et al., 2012). These findings align with flood impact assessments in Jambi and Riau (Mahendra et al., 2023).

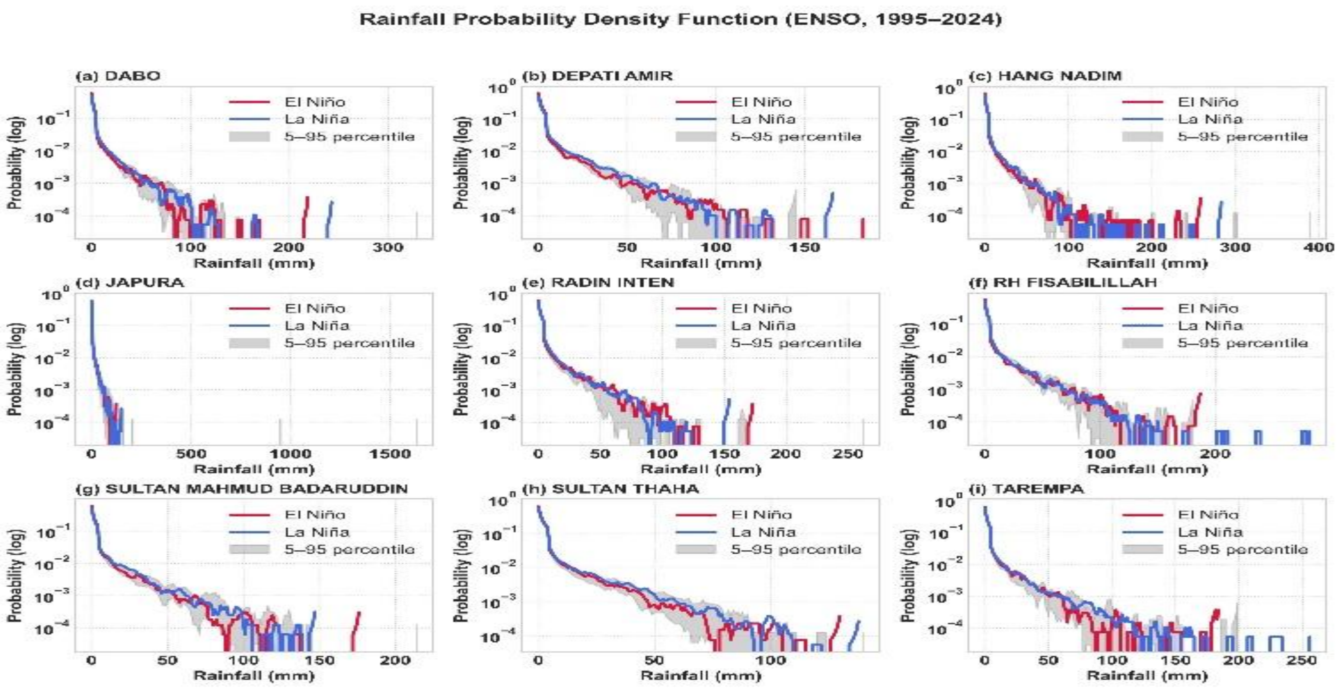

Figure 3. Characteristics of daily rainfall probability distribution in Sumatra's peatland areas during El Niño and La Niña phase

The response to IOD is similarly consistent: positive IOD yields a distribution resembling El Niño (dry), while negative IOD tends to increase the frequency of moderate rainfall, although its effect is weaker than that of La Niña (Kurniadi et al., 2021; As-syakur et al., 2014). Spatial differences are also evident: inland stations exhibit sharper responses to ENSO and IOD, whereas island stations (e.g., Tarempa and Dabo) show more moderate distributional changes, likely due to maritime thermal moderation that stabilizes atmospheric moisture (Marpaung et al., 2012). Spatially, inland stations show sharper distributional shifts compared to coastal and island stations, likely due to reduced maritime influence and greater sensitivity to continental-scale atmospheric anomalies. This inland-coastal gradient has been observed in other regional studies (Prakoso et al., 2021; Fitriani et al., 2023).

Notably, stations Japura and Hang Nadim display the highest extreme intensity ranges (up to 1600 mm/day in the PDF plots). While this value is likely a statistical outlier or binning artifact, a more robust interpretation focuses on the 95th percentile range, which still indicates substantially higher potential for extreme rainfall in eastern coastal regions compared to other areas.

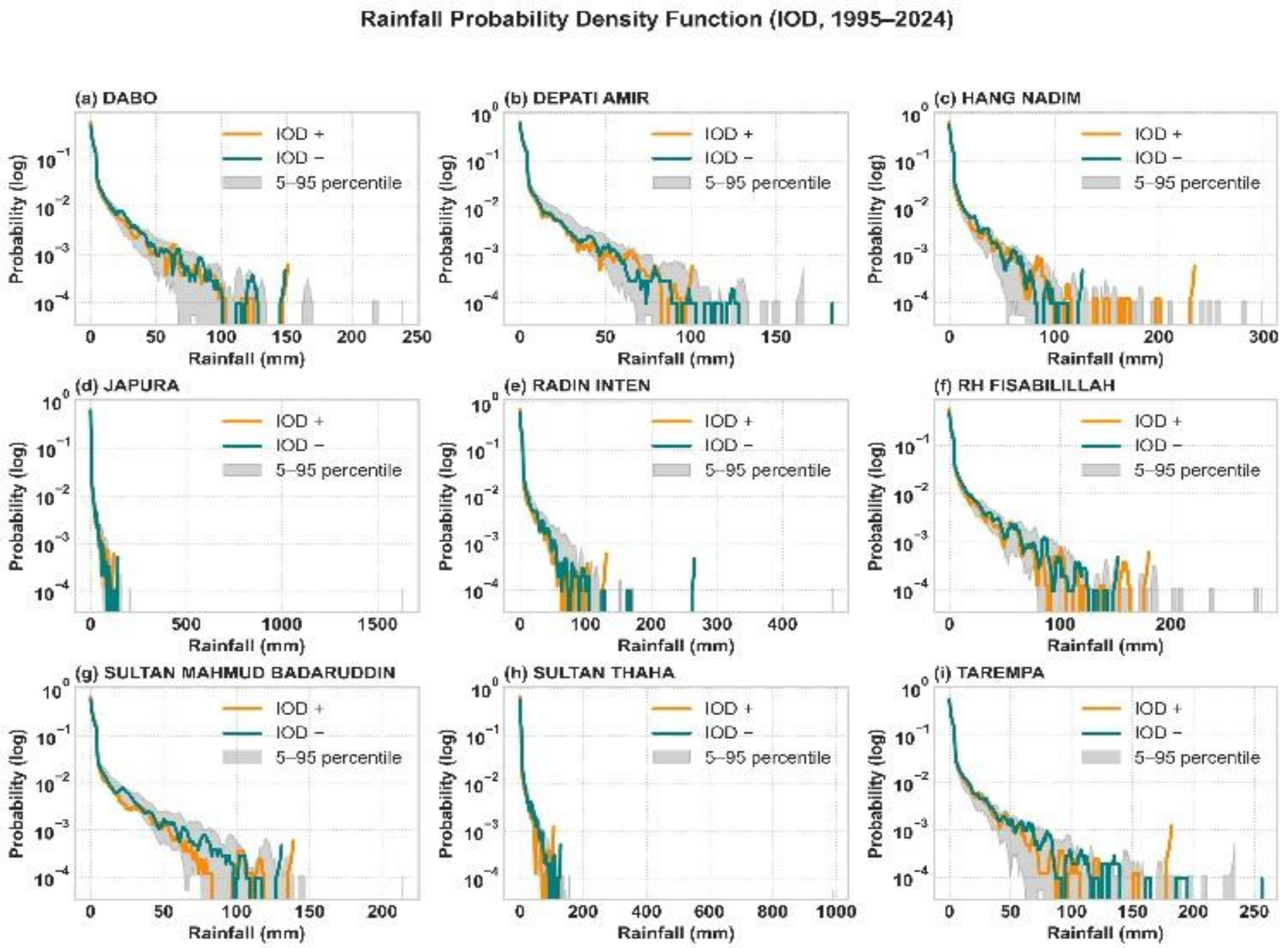

Figure 4. Characteristics of daily rainfall probability distribution in Sumatra's Peatland areas during positive and negative IOD phases

These findings underscore that changes in hydrometeorological disaster risk are not solely determined by shifts in mean rainfall, but by alterations in the shape of the probability distribution itself. During El Niño/positive IOD, drought risk escalates not merely because rainfall decreases, but because the frequency of very low rainfall intensities increases exponentially. Conversely, during La Niña, flood risk rises due to a surge in the probability of extreme rainfall events—even if the mean rainfall increase is modest.

Conclusion

Overall, this study successfully elucidates the frequency and intensity characteristics of daily rainfall in Sumatra's peatland regions and their responses to ENSO and IOD phases over the 1995–2023 period. The results show that daily rainfall is generally right-skewed, with the highest frequency occurring at low intensities (< 20 mm/day). During El Niño and positive IOD phases, the distribution shifts leftward—indicating a dominance of very low rainfall intensities that heighten the risk of drought and peatland fires—whereas La Niña broadens the right tail of the distribution, thereby increasing the probability of extreme rainfall events. Specifically, El Niño increases dry days by 17% and reduces extreme rainfall by over 60%, while La Niña increases extreme rainfall occurrence by nearly 75%. Although these response patterns are spatially and physically consistent, two key components outlined in the original research proposal—seasonal analysis (JJA, SON, DJF, MAM) and formal statistical significance testing (Bootstrap and Permutation Test)—have not yet been fully implemented. This constitutes the primary limitation in the quantitative validation of the findings. Future work should apply seasonal stratification and inferential statistics to formally test the significance of distributional shifts. Moving forward, integrating these results into a climate-informed early warning system represents a strategic step toward mitigating hydrometeorological disasters in Sumatra's highly vulnerable peatland ecosystems.

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Author Contributions
Conceptualization and methodology, writing–original draft preparation, supervision, M.I.; software and validation, K.S. and N.K.; formal analysis and data curation, M.I. and K.S.; writing – review and editing, M.I., K.S., and N.K.; visualization, K.S.

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Conflicts of Interest
The authors declare that there is no conflict of interest in this article.

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