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Dynamics of Extreme Drought and Extreme Wet in Indonesia: Analysis of Frequency, Trends, and Spatial Distribution 1995–2024

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ABSTRACT

The climatological pattern of rainfall and the occurrence of extreme drought and extreme wet in Indonesia are influenced by monsoon dynamics, topography, and Sea Surface Temperature Anomalies (SSTA) in the Pacific and Indian Oceans. Although studies on extreme droughts in Indonesia exist, none have quantified the spatial frequency of extreme drought and rainfall events. This study aims to determine the frequency and trend of extreme drought and extreme rain in Indonesia during 1995–2024. Gridded precipitation data from the Global Precipitation Climatology Center (GPCC) with 0.5° resolution were used. Frequencies of extreme drought and extreme wet were calculated using the Standardized Precipitation Index (SPI), while trends were estimated from the Poisson Regression slope. Frequency and trend were computed for the grid to represent spatial distributions. SPI results at 3, 6, and 12-month scales show Sumatra, Kalimantan, and Papua experienced extreme droughts 8–12 times, with varying frequencies. Extreme droughts were widespread in eastern Indonesia during the dry season (JJA and SON), with longer persistence in SPI-6 and SPI-12. In contrast, extreme wet events occurred more frequently in western and central Indonesia, during the rainy season (DJF), when the western monsoon transported moisture from the Indian Ocean.

1. INTRODUCTION

Indonesia is a maritime region (Hamada et al., 2002) located between the continents of Asia and Australia. As is known, Asia and Australia are two of the world's major monsoon regions, characterized by the Asian monsoon and the Australian monsoon. The monsoon itself is a change in wind direction that can bring moist and dry air. This monsoon plays a significant role in Indonesia's rainfall patterns (Darlan et al., 2020; Hermawan et al., 2019; Mursidi & Sari, 2017). When the Asian monsoon occurs, winds blow from the Asian continent towards Australia, carrying moist air through Indonesia, resulting in a rainy season for Indonesia from December to February (DJF) and March to May (MAM). Conversely, when the Australian monsoon occurs, winds blowing from Australia towards Asia carry dry air through Indonesia, resulting in Indonesia experiencing a dry season, lasting from June to August (JJA) and September to November (SON).

In addition to the monsoon cycle, the dry-wet pattern in Indonesia is also greatly influenced by the phenomenon of ocean-atmosphere interaction in the form of sea surface temperature anomalies (SSTA) (Hendon, 2003; Mubarrok & Jang, 2022). This condition is very lifelike considering Indonesia's geographical location between the Indian Ocean and the Pacific Ocean. When SSTA occurs in the Pacific Ocean (El Niño and La Niña), Indonesia will experience a longer dry season or a wetter season. This condition is even worse if the SSTA also occurs in the Indian Ocean, called the Indian Ocean Dipole (IOD); a positive IOD prolongs the dry season, while a negative IOD prolongs the wet season. History records several extreme droughts that are closely related to the El Niño phenomenon and positive IOD, including the droughts of 1997/98 (Jim, 1999), 2015/16 (Lestari et al., 2018; Supari et al., 2016), and 2019 (Iskandar et al., 2022). In addition, several extreme rainfall events closely related to La Niña and negative IOD occurred in 2010. Indonesia also experienced extreme wet in 2022, particularly in the eastern region of Kalimantan (Hermawan et al., 2025), and this trend has been ongoing since 2008 (Ramadhan et al., 2024).

As a hydrometeorological disaster, extreme drought and extreme wet certainly have an impact on Indonesia (Hendon, 2003). The impacts are not only national in scale, but can also extend internationally, primarily when extreme drought occurs. When extreme drought occurs, the subsequent impact is forest and land fires (Field et al., 2016), which, of course, cause haze to reach neighboring countries, such as Malaysia. Even the fires that occurred in 2002, 2006, 2009, 2015, and 2019 were closely related to the El Niño Southern Oscillation (ENSO) and IOD (Dafri et al., 2021). Of course, in those years, extreme droughts preceded the fires. This haze is also hazardous to the human respiratory system.

The severity of the impact of this hydrometeorological disaster underscores the importance of early prevention in the form of mitigation (Keil et al., 2007), mainly when El Niño (Sze et al., 2019) and positive IOD occur, because when El Niño and positive IOD occur, extreme drought occurs, which usually has an impact on hydrometeorological disasters. Mitigation requires an initial investigation into the history of the disaster, both in the form of an analysis of the frequency of occurrence and trends over a specific time. This study aims to quantify the frequency, trend, and spatial distribution of extreme drought and wet events across Indonesia from 1995–2024. The analysis of the frequency and trends of extreme wet based on SPI-3, SPI-6, and SPI-12 is novel because SPI is typically used to analyze drought, whether on a light, moderate, or extreme scale.

2. METHOD

2.1 Data

This study utilizes Global Precipitation Climatology Center (GPCC) data with a 0.5° resolution from 1995 to 2024. GPCC itself is data that is widely used in research related to Hydrometeorology, including Spinoni et al. (2019), Suhadi et al. (2023), Supari et al. (2016), and Torsri et al. (2022). In the research of Torsri et al. (2022), GPCC showed agreement with rainfall data from local (Thai Meteorological Department) stations. Specifically for Indonesia region, Supari et al. (2016) showed that GPCC data is more accurate in representing rainfall observations than CRU data.

Table 1 SPI Value Category.

SPI Value	Category
SPI > 2	Extremely Wet
1.55 ≤ SPI ≤ 1.99	Very Wet
1.0 ≤ SPI ≤ 1.49	Moderately Wet
-0.99 ≤ SPI ≤ 0.99	Near Normal
-1.0 ≤ SPI ≤ -1.49	Moderately Drought
-1.55 ≤ SPI ≤ -1.99	Very Drought
SPI < -2	Extremely Drought

2.2 Calculation of Frequency of Extreme Drought and Extreme Rainfall

Before calculating the frequency and trend, we calculate the rainfall anomaly for each grid in Indonesia using SPI. The SPI is a normalized rainfall index, calculated by fitting rainfall data into a gamma distribution function. The gamma distribution function is then transformed into a cumulative distribution function to obtain an index ranging from -2 to 2. Details of the SPI calculation can be found in Pramudya & Onishi (2018), Suhadi et al. (2023), and WMO (2012). The results of the SPI calculation, for SPI-3, SPI-6, and SPI-12, are presented in the form of numbers indicating the anomaly in accumulated rainfall, as shown in Table 1. As a method recommended by the World Meteorological Organization (WMO), SPI has been widely used to identify drought, as seen in Adeola et al. (2021), Adisa et al. (2021), Bonacci et al. (2021), Kamruzzaman et al. (2019), Reyes et al. (2022), and Sharma et al. (2022).

After calculating the SPI, the frequency of extreme drought and extreme rainfall is determined based on equation (1) as follow

$$f = \frac{n}{t} \quad (1)$$

where n is the extreme drought (SPI < -2) and extreme wet (SPI > 2), and t is the observation time (30 years).

2.3 Calculation of Trends of Extreme Drought and Extreme Rainfall

After the frequency, the trend of extreme drought and extreme wet is calculated by Poisson Regression. The Poisson regression model is basically a regression model characterized by data on events that occur randomly and rarely without any particular variables influencing them (Cupal et al., 2015). In addition to Cupal et al. (2015), who used poison regression to analyze trends in rare events (floods), Getaneh et al. (2024) also used the same regression to analyze trends in neonatal mortality in Ethiopia. Based on the characteristics of this poison regression, we use it to calculate the trends of extreme drought and extreme rainfall, because these two phenomena are random and rarely occur. Poison regression is shown in equation (2).

$$\log(\mu_t) = \beta_0 + \beta_1 t \quad (2)$$

where μ_t is the average occurrence of extreme drought and extreme wet at time t. β_0 is the log of the average occurrence of extreme drought and extreme wet at the initial condition ($t = 0$), while β_1 is the slope, which shows an increasing trend if the value is positive, and a decreasing trend if the value is negative.

3. RESULTS AND DISCUSSION

3.1 Rainfall Climatology

Indonesia's rainfall climatology over the past 30 years is shown in Figure 1. Over the past 30 years (1995-2024), Indonesia's rainfall has ranged from 3mm/month to 575mm/month. Generally, rainfall in Indonesia occurs from November to April, while drought typically occurs from May to October, as observed by Mulsandi et al. (2024). This dry-wet season period shows that Indonesia's rainfall is predominantly influenced by the Asian-Australian monsoon (Aldrian & Susanto, 2003; Ariska et al., 2024; Chang et al., 2005).

This climatology also indicates that during the dry season, the Nusa Tenggara Islands, located south of the equator, receive low rainfall. Meanwhile, Sumatra begins its dry season in May, peaking in January, Java in May, peaking in October, and Kalimantan and Sulawesi in June, peaking in August. Sumatra receives relatively high rainfall in September and October. Several extreme droughts (Iskandar et al., 2017, 2022; Lestari et al., 2018) and extreme rainfall (Hermawan et al., 2019; Mubarrok & Jang, 2022) have been identified during these months, particularly from September to November. Unlike other regions, Papua, located at coordinates 140°E; 6°S, generally receives higher rainfall than other regions, as also shown in previous research (Chang et al., 2005). This condition is understandable, as the region has a higher topography than other regions.

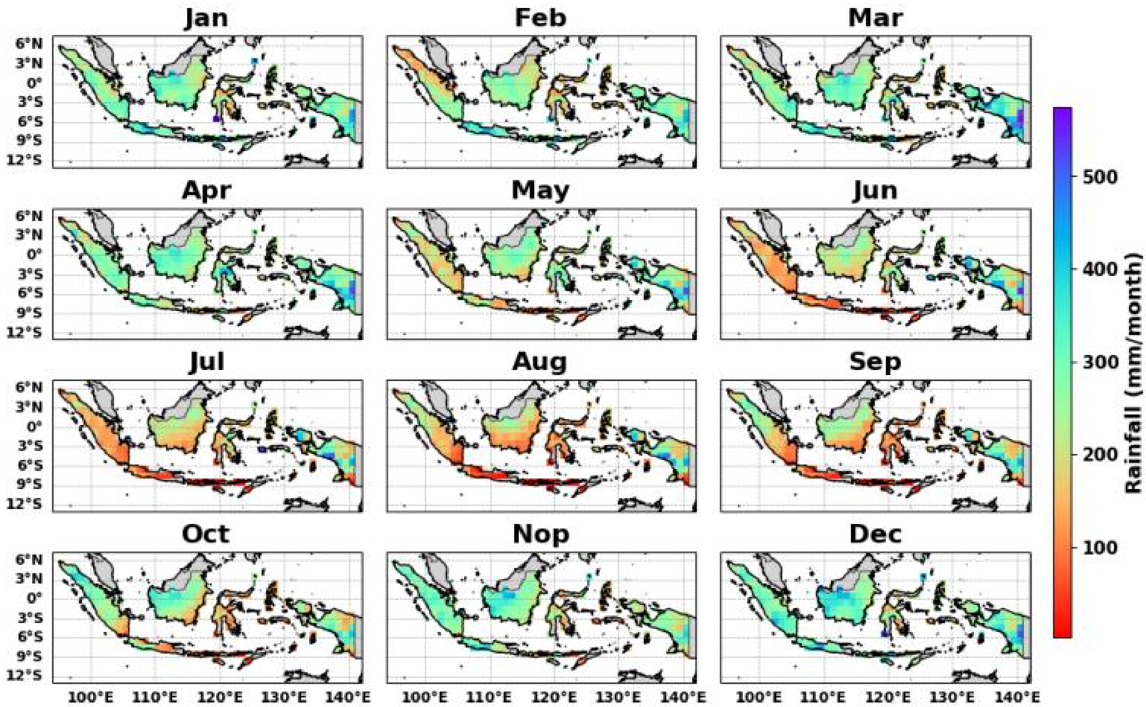

Figure 1 Indonesia Rainfall Climatology over 30 years (1995-2024).

3.2 Extreme Drought and Extreme Wet Frequencies

In general, the number of extreme droughts and extreme wet events over the past 30 years (1995-2024) ranged from 0 to 12 (Figure 2), with a distribution from western to eastern Indonesia. The frequency of extreme droughts in SPI-3 is more widespread in Papua, particularly in West Papua, compared to SPI-6 and SPI-12. This indicates that Papua experiences extreme droughts more frequently during seasonal periods. Although Papua receives higher rainfall than other regions throughout the year, extreme droughts in this region (primarily based on SPI-3) tend to be higher than in other regions. This indicates that extreme droughts in Papua are predominantly seasonal, and this condition is connected with El Niño and positive IOD (Nurdiati et al., 2023). In addition, extreme droughts based on SPI-12 in the western to central regions of Indonesia (especially Sumatra and eastern Kalimantan) are more frequent based on SPI-6 and SPI-3. This drought in Sumatra has also been identified by Suhadi et al. (2023). In that study, the west coast of Sumatra also experiences extreme droughts more frequently, primarily based on SPI-12, and these extreme droughts are connected with El Niño and positive IOD (Suhadi et al., 2023). During an El Niño event, seawater evaporation occurs only in the central to eastern Pacific Ocean, resulting in rainfall in this region, while Indonesia experiences drought. Similarly, during a positive IOD, evaporation occurs only in the western Pacific Ocean, potentially causing rainfall in this region, while Indonesia experiences a rainfall deficit.

In addition to the different drought frequencies based on SPI-3, SPI-6, and SPI-12 in several regions of Indonesia, it turns out that the Sulawesi and Java Islands (except West Java) experience the same number of extreme droughts (based on SPI-3, SPI-6, and SPI-12), as does the Nusa Tenggara region, as has been known in previous research (Kuswanto et al., 2018, 2021). Kuswanto et al. (2018) and Kuswanto et al. (2021) also show that the return period of the Nusa Tenggara region experiencing extreme drought is less than 4 years. The extreme drought in this area is connected to El Niño (Supari et al., 2018). These results indicate that the region is very vulnerable to extreme droughts both on a seasonal, semi-annual, or annual scale.

In line with the frequency of extreme droughts (Figure 2.a-c), the frequency of extreme wet (Figure 2 d-f) shows a reasonable correlation. This condition occurs because a region exhibiting a high frequency of extreme droughts typically has a low frequency of extreme rainfall. For example, based on SPI-3, extreme wet in northern Sumatra is more frequent than extreme droughts. Previous research (Darlan et al., 2020) also shows that the North Sumatra region tends to receive higher rainfall, especially in the western part. This pattern is also actual for other regions, as indicated by SPI-6 and SPI-12. Climatologically, the Nusa Tenggara Islands receive low rainfall almost year-round (except December) (Figure 1), yet the frequency of extreme wet in this region is more frequent than extreme droughts. This circumstance suggests that although rainfall in this region is low, high-intensity rainfall also occurs frequently, leading to extreme rainfall events.

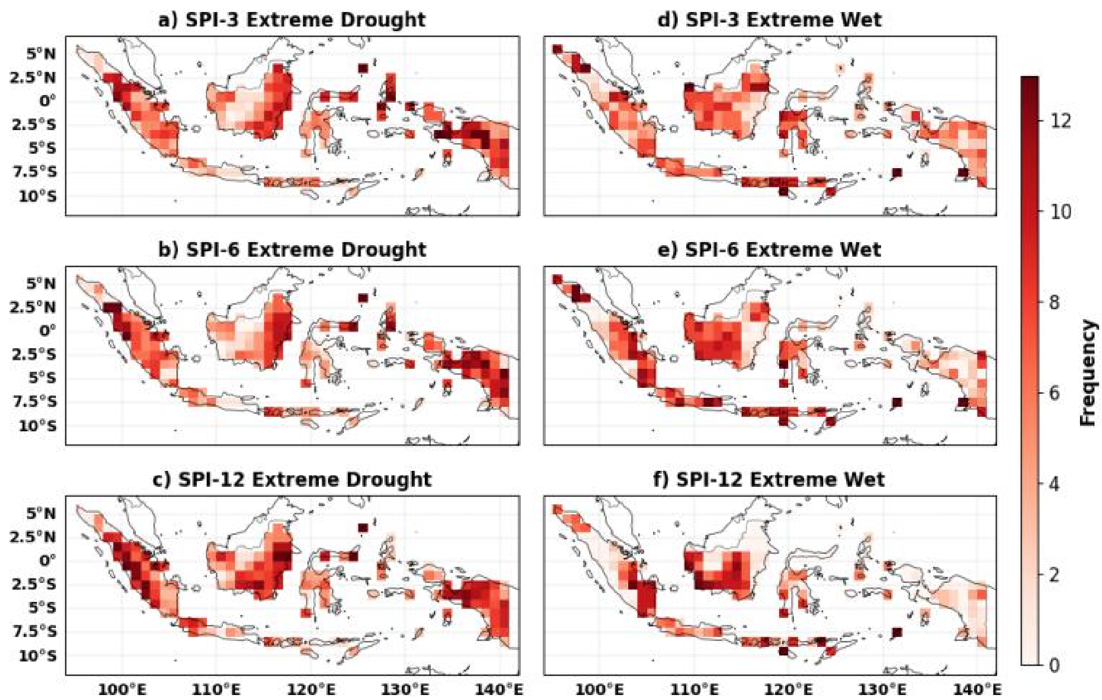

Figure 2 Extreme Drought and Wet Frequency based on SPI-3, SPI-6, and SPI-12.

To examine the distribution of drought and extreme rainfall frequencies in greater detail, we present the results of these frequency evaluations on a seasonal scale, extreme droughts on a seasonal scale in Figure 3, and extreme rainfall in Figure 4. The frequency of extreme droughts, based on SPI-3 (Figure 3.a-d) over 30 years, varies from western to eastern Indonesia. Spatially, Sumatra, Kalimantan, western Java, Nusa Tenggara, northern Sulawesi, and western Papua experience extreme drought more frequently than other regions, especially during the DJF, which decreases in JJA and increases again in SON. Kuswanto et al. (2021) also pointed out that extreme drought in Nusa Tenggara is higher than in other regions. This is certainly related to the recurrence period of extreme drought in the region, which ranges from 2 to 4 years. Meanwhile, eastern Indonesia, particularly Papua, experiences an increase in the frequency of droughts from DJF to JJA, with the peak occurring in SON. This Condition is consistent with the rainfall climatology in the region.

Based on SPI-6 (Figure 3.e-h), the frequency of extreme drought is higher in western Indonesia during DJF and MAM. Meanwhile, in JJA, the frequency of extreme drought is higher than in other regions in central to eastern Indonesia. In addition, based on SPI-12 (Figure 3.i-l), the frequency of extreme drought based on SPI-12 varies each season. In DJF, a high frequency of extreme drought occurs in almost every region of Indonesia, except for a small part of Kalimantan, southern Sumatra, and the island of Java. In MAM, the frequency of extreme drought in western to central Indonesia is higher than in DJF (the frequency in this period is the highest) and decreases again in JJA and SON. The Papua region experiences the highest frequency of extreme drought in DJF, which then decreases in MAM to JJA, then increases again in SON. The high frequency of extreme drought in eastern Indonesia, especially in JJA and SON, is closely related to the ENSO and IOD phenomena (Suhadi et al., 2023), as well as negative SST anomalies in Indonesian waters themselves, which in turn trigger a reduction in water mass convection in the Indonesian archipelago (Iskandar et al., 2017).

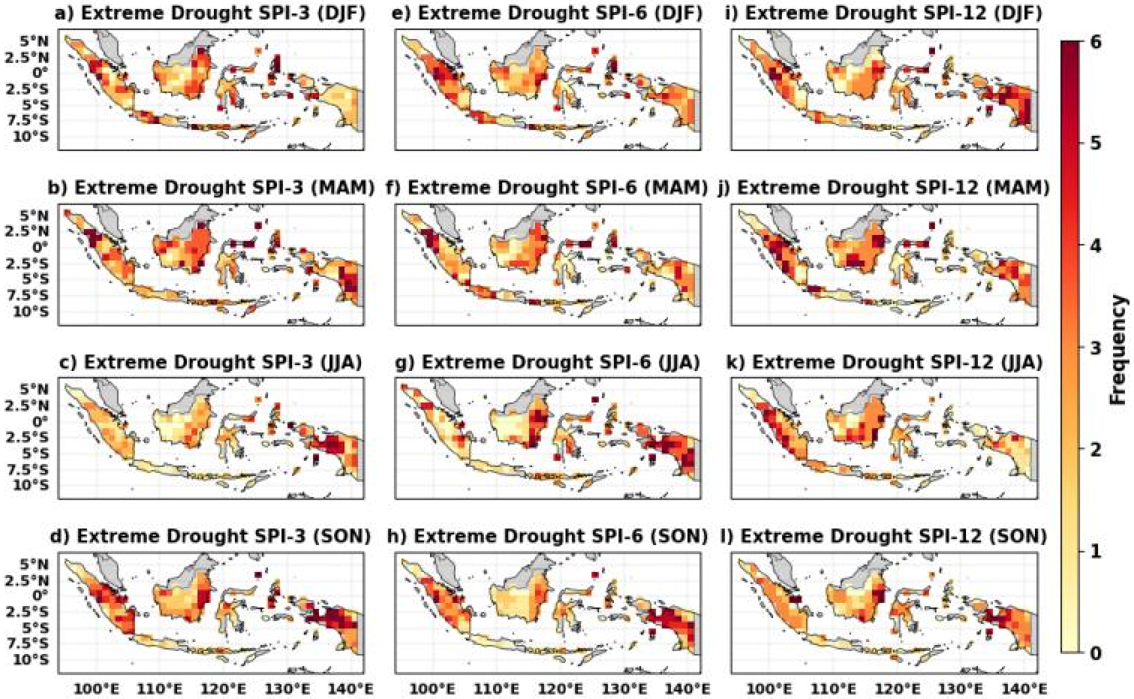

Figure 3 Seasonal Extreme Drought Frequency based on SPI-3, SPI-6, and SPI-12.

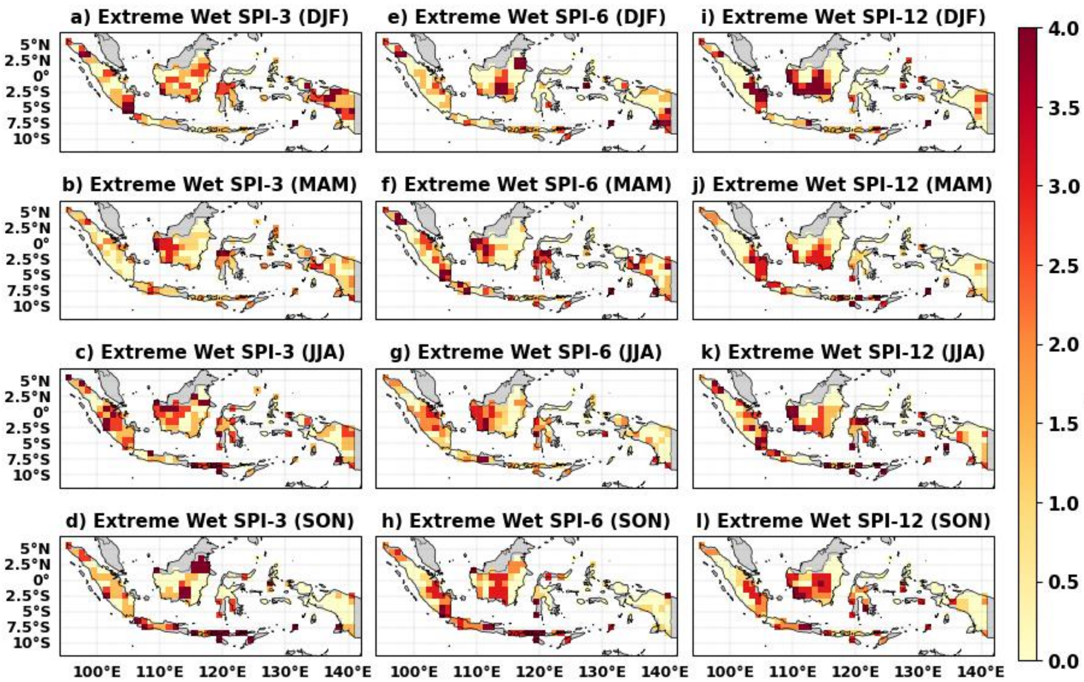

Figure 4 Seasonal Extreme Wet Frequency based on SPI-3, SPI-6, and SPI-12.

The frequency of extreme wet, as indicated by the SPI, in each season is shown in Figure 4. In general, the frequency of extreme wetness based on SPI varies by season, as seen in SPI-3 (Figure 4.a-d), SPI-6 (Figure 4.e-h), and SPI-12 (Figure 4.i-l). When compared to extreme drought, the frequency of extreme wet shows consistent results. This condition is evident from the high and low frequencies of extreme drought and extreme wet. For example, the frequency of extreme wet in DJF (Figure 4.a) (based on SPI-3) in southern Lampung is higher than in other regions, so the frequency of extreme drought (Figure 3.a) in that region is lower than in others. However, based on SPI-12 in MAM (Figure 4.j), in addition to frequently experiencing extreme drought, the southern region of Kalimantan also experiences extreme wet more often (Figure 3.j) than other regions. Previous research (Marzuki et al., 2023) also showed an increase in extreme rainfall in Kalimantan. Marzuki et al. (2023) showed that extreme rainfall in Kalimantan has increased, particularly based on five-day rainfall data.

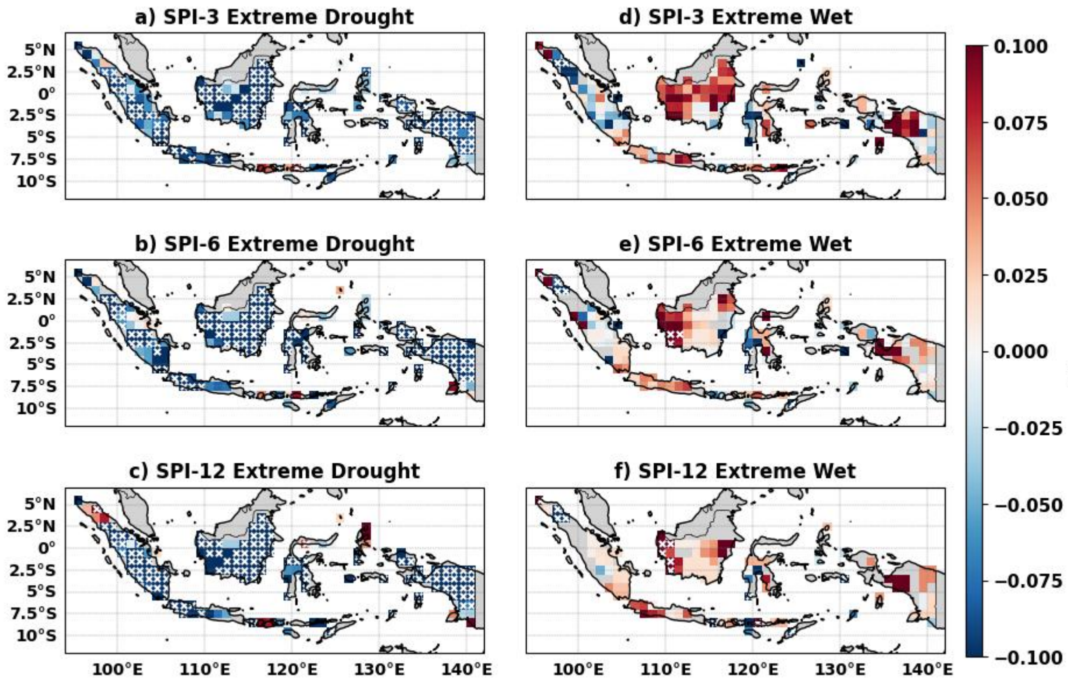

Figure 5 Trend of Extreme Drought and Wet Frequency based on SPI-3, SPI-6, and SPI-12. A white cross indicates the 95% Significance Level.

3.3 Trend of Extreme Drought and Wet Frequencies

The increasing and decreasing trends in the frequency of extreme drought and extreme wet are shown in Figure 5. Over the 30 years, the increase and decrease experienced a trend of 0.1 or 0.03 per decade. Based on these results, it can be seen that the trend of extreme drought (Figure 5.a-c) has experienced a significant decrease in almost all regions of Indonesia. Previous studies (Saidah et al., 2023) also showed a decrease in extreme drought since 1990, especially in eastern Indonesia. This decrease in extreme droughts is certainly related to increased La Niña activity, which results in increased sea surface temperatures around Indonesia (the western Pacific region), ultimately increasing the potential for rainfall in Indonesia. However, the trend of extreme wet did not immediately experience a significant increase. Based on SPI-6 (Figure 5.e) and SPI-12 (Figure 5.f), only a small part of southwest Kalimantan experienced a significant increase in extreme wet. Based on SPI-3 (Figure 5.d), only a small part of northern Sumatra experienced a decrease in extreme wet, and this trend appears to be consistent, as indicated by SPI-6 and SPI-12.

Similar to the frequency, the trends of extreme drought and extreme wet events in each season are analyzed, as shown in Figure 7 and Figure 8. The SPI-3 seasonal analysis (Figure 6.a-d) shows a significant decrease in the extreme drought trend in Papua during MAM and JJA. Additionally, a significant decrease in the central part of Sumatra occurs during the DJF and MAM periods, and a significant trend decrease in eastern Kalimantan occurs during the SON period. This increase was also found in previous studies (Marzuki et al., 2023). The SPI-3 seasonal analysis also indicates that only one grid point, located in the center of Sumatra, exhibits a significant decrease in the extreme wet trend. This decrease in the trend occurs during MAM (Figure 6.f). This situation indicates that there has been almost no significant increase or decrease in the extreme wet trend in Indonesia during the 1995-2024 period.

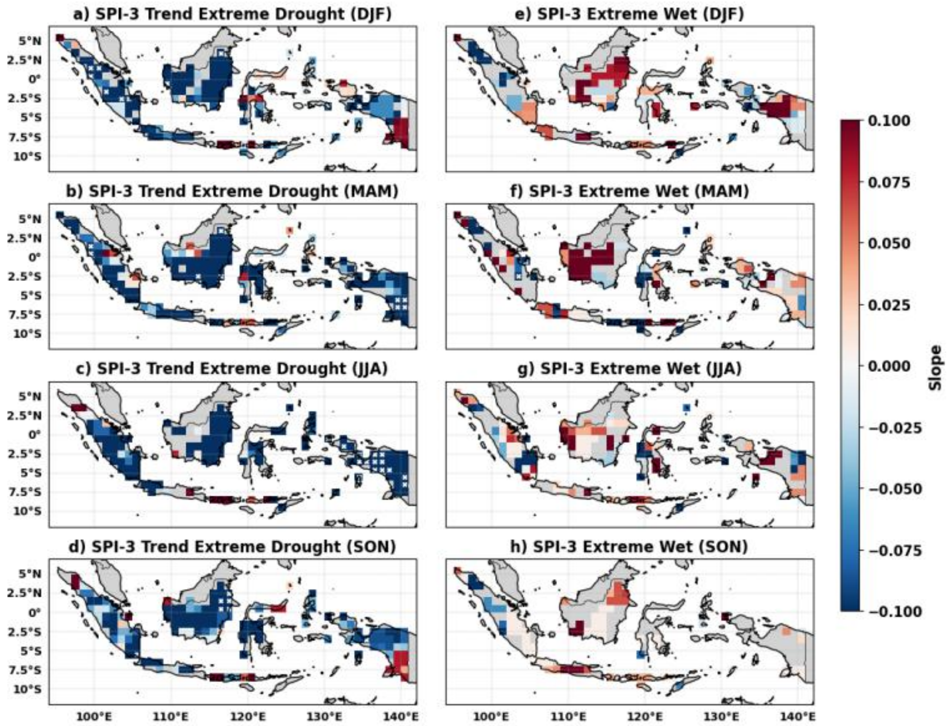

Figure 6 Seasonal Trend of Extreme Drought and Wet Frequency based on SPI-3. A white cross indicates the 95% Significance Level.

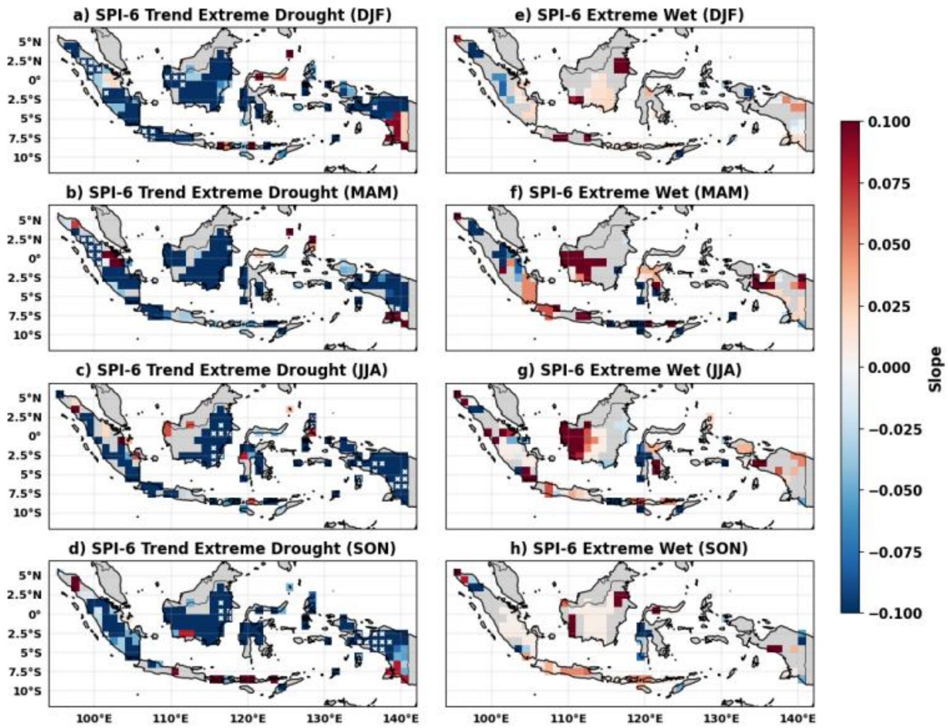

Figure 7 Seasonal Trend of Extreme Drought and Wet Frequency based on SPI-6. A white cross indicates the 95% Significance Level.

Similar to the seasonal trend in the frequency of extreme droughts based on SPI-3, the frequency of extreme droughts based on SPI-6 (Figure 7.a-d) decreased each season. However, this decrease did not occur in every region of Indonesia. Western Indonesia, particularly north of the equator of Sumatra and western Kalimantan, experienced a significant decrease in extreme droughts in DJF and MAM (Figure 7.a-b). In JJA and SON (Figure 7.c-d), the decrease in extreme droughts occurred in eastern Kalimantan and central and eastern Papua. Based on SPI-6, no significant seasonal trend of extreme rainfall was detected.

Based on Figure 8. a-b, it can be seen that a significant decrease in the extreme drought trend (based on SPI-12) in DJF predominantly occurs in central Papua. Meanwhile, in Sumatra and Kalimantan, only one grid point was detected that exhibited a decreasing trend, particularly during DJF. In MAM and JJA, a significant decrease in extreme drought is typically detected in central Sumatra and Kalimantan. In SON, a significant decrease in extreme drought is again observed in central Papua, as is the case in DJF. Similar to the results of the seasonal analysis based on SPI-3 and SPI-6, the results of the seasonal analysis of SPI-12 also do not show a significant increase or decrease in the extreme rainfall trend.

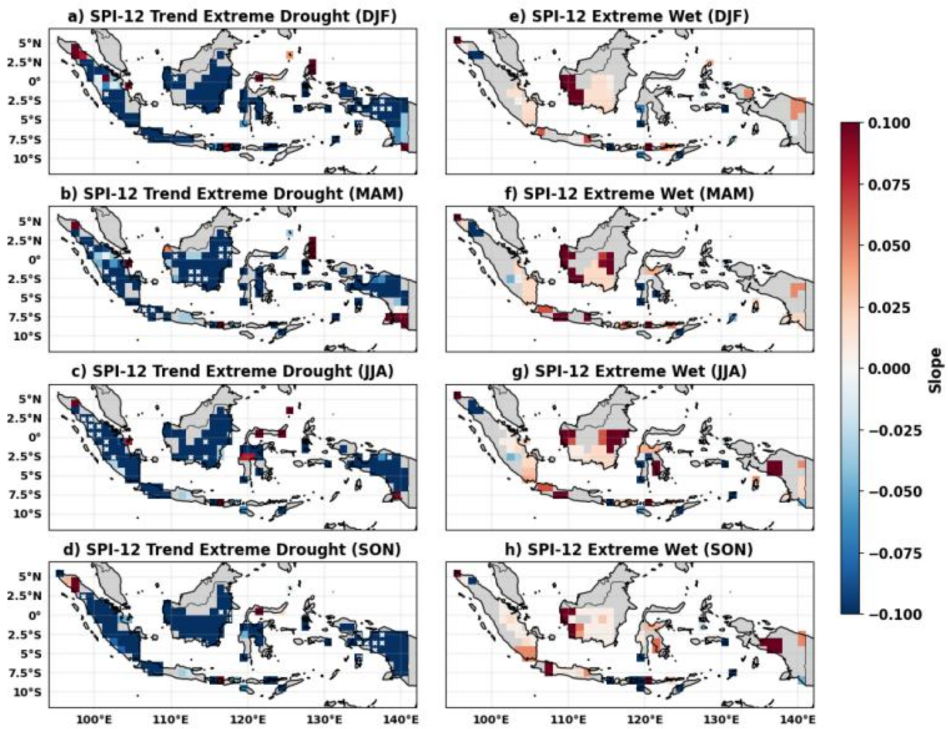

Figure 8 Seasonal Trend of Extreme Drought and Wet Frequency based on SPI-12. A white cross indicates the 95% Significance Level.

4. CONCLUSION

Monsoon dynamics, topography, and global climate phenomena, such as ENSO, strongly influence the climatological patterns of rainfall and extreme events (including drought and wet periods) in Indonesia. From 1995 to 2024, areas of Sumatra, Kalimantan, and Papua experienced extreme droughts approximately 8 to 12 times. The distribution of the most frequent droughts is generally spread by season, based on SPI-3, SPI-6, or SPI-12. Extreme droughts tend to be more widespread in eastern Indonesia during the dry season (JJA and SON), with longer persistence in SPI-6 and SPI-12. Conversely, extreme wet occurs more frequently in western and central Indonesia, especially during the rainy season (DJF), in line with the arrival of the West Monsoon, which brings moisture from the Indian Ocean. These differences in spatial patterns between extreme drought and extreme wet indicate the division of hydrometeorological risk zones in Indonesia. Drought-prone areas, such as Nusa

Tenggara, require adaptation strategies related to irrigation and water reserves, while areas prone to extreme wet, like West Sumatra and Kalimantan, need to focus on flood and landslide mitigation.

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