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Analysis of Rainfall Patterns in Papua Using The Empirical Orthogonal Function

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Abstract
Indonesia, as a tropical maritime country, experiences dry and rainy seasons influenced by geographical location, topography, winds, and climate phenomena such as ENSO and IOD. Although extensive research on rainfall patterns in Indonesia exists, specific studies on Papua remain limited. This gap leads to insufficient understanding of Papua's rainfall characteristics and dynamics, including dominant patterns and variability factors. This study aims to analyze rainfall patterns in Papua using the Empirical Orthogonal Function (EOF) method to identify dominant patterns and key modes of variability systematically. The EOF method is applied to extract dominant patterns from complex datasets, enabling spatial and temporal analysis of rainfall variability in the region. Analyzing rainfall patterns in Papua (1981–2015) using EOF combined with Machine Learning reveals that average rainfall intensity in Papua ranges from 0–9 mm per month. The EOF analysis identifies three principal modes explaining 62.53 percent, 11.39 percent, and 7.01 percent of total variance, respectively. EOF1 indicates dominant positive anomalies, while EOF2 and EOF3 show mixed positive and negative anomalies. Furthermore, rainfall variability in Papua is significantly influenced by interactions between the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO), where positive IOD and El Niño phases contribute to dry conditions and reduced rainfall, while negative IOD and La Niña phases lead to wet conditions and increased rainfall.

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1. Introduction

One of the weather components that most affects human activities is rainfall [1]. Indonesia, as an archipelago flanked by two continents and two large oceans, has a tropical climate with two main seasons: dry and rainy. Rainfall patterns in Indonesia are not only influenced by the monsoon; there are also local and equatorial rainfall patterns [2][3]. Changes in the average weather patterns on earth or in a particular region over the long term are called climate change. Studying local climate, it is important to understand how local atmospheric conditions and the overall climate system affect it [4]. Climate change can result in erratic rainfall patterns, with some regions experiencing extreme rainfall and flooding, while others experience prolonged drought [5]. These natural disasters have the potential to destroy homes, infrastructure, and cause loss of life [6]. As a result, it is imperative to take action to reduce the impact of these events and prepare for whatever may happen.

Indonesia has conducted numerous studies on rainfall analysis, such as the research by Setiawan, Dedi in 2021, which states that the regions of Papua and West Papua are areas with the highest levels of rainfall [7].

The research by Tulak, Noper et al. [8] on daily rainfall patterns in Jayapura City (2001-2018) utilized MATLAB and Excel. The objective was to identify cycles, trends, and extreme rainfall events, as well as to understand changes in rainfall patterns in this region. The findings indicate that the increasing trend of rainfall is accompanied by occurrences of extreme rainfall at the beginning and end of the year, with a frequency of 1 to 5 times per year. The research conducted by Edowati, Desi N in 2023 [9] in Nabire Regency, Central Papua Province, reveals that the results of the linear regression analysis on rainfall and temperature indicate annual changes. Rainfall has decreased by 0.782 mm per year, while temperature has increased by 0.1436 °C each year. Overall, the intensity of rainfall and temperature tends to change annually, contributing to climate change. Based on several studies, each region has different levels of rainfall. High and extreme rainfall often occurs in certain areas, which can lead to hydrometeorological disasters in Papua. Therefore, research on rainfall is essential to understand the climatic conditions in this region.

Papua is located between latitudes 0° 20′ and 10° 42′ N, and longitudes 130° and 151° E. Papua is a tropical and island region with an average rainfall of 2,015.8 mm, with rainfall between 1,500 and 7,500 mm per year. The north coast and central mountains receive the highest rainfall, while the south coast receives the lowest. With increasing altitude, temperatures vary. Rainfall levels on the island of Papua are highly variable and different. Therefore, it is very important to always check the latest weather forecasts.

Indonesia has conducted many studies on rainfall pattern analysis. However, no one has examined and analyzed rainfall patterns specifically on the island of Papua. This research is important because the Papua region has unique and complex rainfall characteristics, yet there is still a lack of in-depth studies related to rainfall patterns. The absence of comprehensive information leads to a limited understanding of the spatial and temporal variability of rainfall, which is crucial for mitigating hydrometeorological disasters such as floods and landslides, as well as for climate-based development planning. Furthermore, the available rainfall data is often limited in scope due to an inadequate number of observation stations, necessitating new approaches such as the utilization of modern analytical methods. Therefore, based on the explanation above, the author is interested in conducting research on "Analysis of Rainfall Patterns in Papua Island Using the Empirical Orthogonal Function (EOF) Method." The Empirical Orthogonal Function (EOF) method is applied as a multivariate analysis technique aimed at identifying and extracting dominant patterns that explain the main variability in complex datasets. Thus, the application of the EOF method is expected to provide a deeper and more thorough understanding of the characteristics and dynamics of complex rainfall patterns in the Papua region, as well as identify key modes of variation influencing rainfall distribution in this area. The expected benefits of this research include identifying areas with high, moderate, and low rainfall patterns on Papua Island. This study not only identifies rainfall patterns but also analyzes their spatial and temporal variability, providing new insights into how global climate factors such as ENSO and IOD influence rainfall in Papua. The availability of updated data and information on rainfall patterns can serve as a reference for the people and the government of Papua Province in developing commodities that align with the current climatic conditions of Papua Island.

2. Methods

This study employs a descriptive quantitative approach, chosen for its emphasis on numerical data derived from the research location. The focus is on analyzing rainfall patterns in Papua over a span of 408 months, covering the period from January 1981 to December 2015. Rainfall data utilized in the research was sourced from the website https://sacad.bmkg.go.id/ID/ . The data in this study uses NeTCDF format.

2.1 Empirical Orthogonal Function (EOF)

The Empirical Orthogonal Function (EOF) method is a time series data analysis technique used to separate the signal into two components, the spatial function and the time function. The aim is to identify the dominant spatial patterns in the time series data and sort these patterns by their variance, from largest to smallest [10]. EOF is utilized to identify the primary weather patterns in rainfall data by employing singular value decomposition (SVD) to reduce the data's dimensionality. Before applying principal component analysis (PCA) or empirical orthogonal function (EOF), a crucial initial step is to standardize the data, especially if the variables being analyzed have heterogeneous units or ranges of values.

$$Z = \frac{X - \mu}{\sigma}$$

In this case, X is the original data matrix, μ is the mean vector of each variable, and σ is the standard deviation of each variable used for scaling in data standardization. After standardizing the data, the next step is to calculate the covariance matrix of the standardized data. This covariance matrix measures the shared variation between variables, providing information on how changes in a variable correlate with other variables.

$$C = \frac{1}{N-1} Z^T Z$$

In this formulation, C represents the covariance matrix, Z represents the data that has undergone the standardization process, and N indicates the cardinality of the observation set.

The eigen decomposition of the covariance matrix yields the eigenvalue and eigenvector. The eigenvalue indicates the amount of variance explained by each principal component (PC), while the eigenvector determines the direction of that component in the original feature space.

$$C_v = \lambda_v$$

In eigenanalysis, λ (eigenvalue) indicates the amount of variance explained by each principal component, and v (eigenvector) defines the direction or pattern of variation captured by the principal component in the original data. The overall variance accounted for by all principal components is equal to the total of their eigenvalues.

$$Variasi\ Total = \sum_{i=1}^{n} \lambda_i$$

The fraction of variance accounted for by each principal component (PC) can be quantified as a percentage of the total variance of the dataset.

$$Variansi\ PC_1 = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i}\ X\ 100\%$$

2.2 Analisis Komposit

Composite analysis is an easy and efficient method for recognizing conditions that occur under particular climatic circumstances. Composite Analysis can show the relationship between a phenomenon and key areas around it [11]. ENSO (El Niño-Southern Oscillation) and IOD (Indian Ocean Dipole) composite analysis is a statistical technique used to identify rainfall patterns across different areas of the globe, related to the ENSO and IOD phenomena.

3. Results and Discussion

This research goes in-depth on rainfall patterns in the Papua region by relying on official rainfall data from SACA&D accessed through the website https://sacad.bmkg.go.id/id/. The main focus of this study is to understand how the distribution of rainfall varies across the Papua region within a given time span, as well as to identify possible seasonal trends or patterns. The study area is bounded by 0° to 10° south latitude and 130° to 151° east longitude. This study takes into account the typical geographical and climatic conditions of Papua. Monthly rainfall data collected from the Southeast Asia Climate Assessment and Dataset Store (SACA&D) website for a period of 35 years, between 1981-2015, has been carefully selected to provide a comprehensive picture of rainfall fluctuations over a long period of time.

EOF is used to identify the spatial pattern of rainfall in Papua after the data is cleaned from NaN and missing values are filled using singular value decomposition. The results are visualized as annual rainfall distribution maps. The analysis results are then visualized in the form of rainfall distribution maps (Figure 1).

3.1 Mean of Precipitation

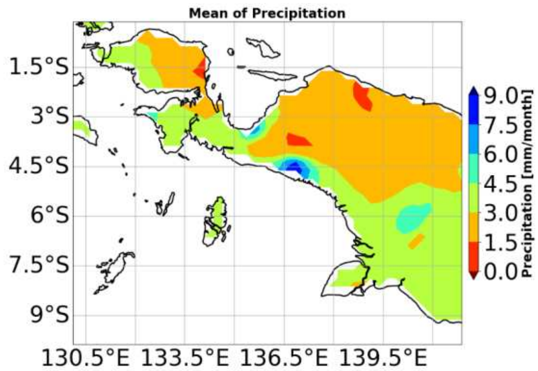


Figure 1. Average Rainfall on Papua Island

Based on the BMKG classification, rainfall intensity in Indonesia is categorized into four groups as shown in Table 1 (*Source:* https://www.bmkg.go.id/)

Table 1. Categorization of rainfall intensity in Indonesia

Rainfall Intensity (mm/month)	Criteria
0-100	Low
100-300	Intermediate
300-500	High
>500	Very High

Figure 1 shows significant spatial variations. The rainfall distribution map uses a color scale to illustrate the spatial variation of rainfall, with dark blue indicating high rainfall and dark red indicating low rainfall. The analysis shows that most areas in Papua experience intermediate rainfall, with Mimika Regency in Central Papua Province identified as the region with the highest monthly rainfall based on the data displayed on the map. This result aligns with previous research conducted by Faisol and his team in 2022, which stated that the average monthly rainfall in West Papua is more than 100 mm [12].

Then research conducted by Presli and the team in 2018 showed that the average rainfall in Papua was 120-200 mm [13]. Both studies show that Papua experiences medium levels of rainfall, which can be seen Table 1 on the classification of rainfall intensity in Indonesia.

3.2 Std of Precipitation

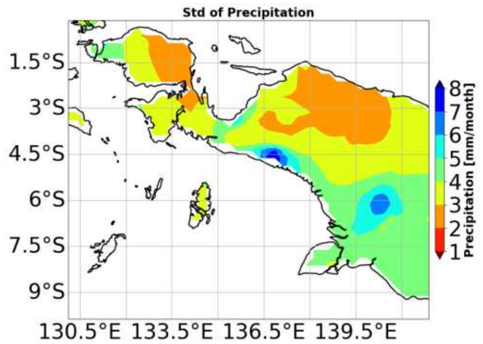


Figure 2. Standard Deviation of Rainfall in Papua Island

The visualization in Figure 2 uses a color scale to show the level of uncertainty of rainfall in Papua. The standard deviation in the Papua region is classified as low to medium level with a range of values of 8-1 mm/month. Mampi district in South Papua and Mimika district in Central Papua show the highest level of rainfall uncertainty. Dark blue color indicates very high rainfall variability, which is mainly found in Mimika district in Central Papua and Mampi district in South Papua, indicating more extreme rainfall fluctuations in these two regions. The standard deviation of rainfall in Papua shows a heterogeneous spatial distribution. Some areas have much higher levels of rainfall variability, indicating more extreme rainfall fluctuations over time than others.

3.3 Monthly Climatology

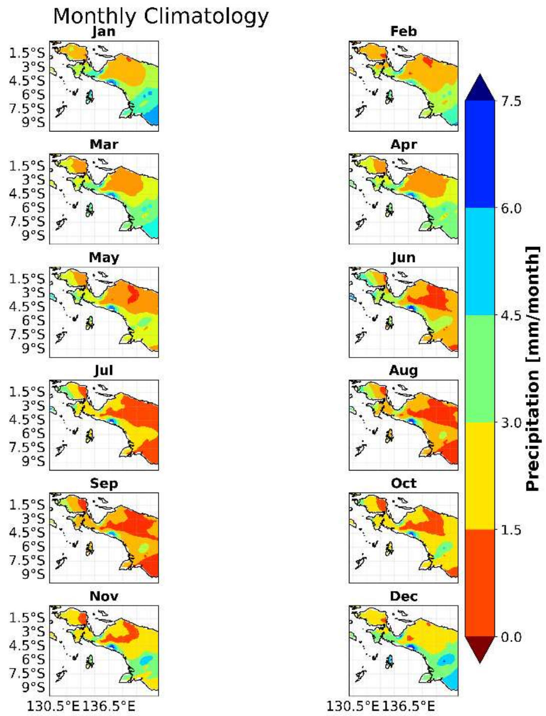


Figure 3. Monthly Climatological Rainfall in Papua Island

Figure 3 shows that most areas in Papua experience relatively low rainfall throughout the year, especially in the June to September period which is the dry season. However, there are exceptions in Merauke Regency which records high rainfall in December and January.

3.4 Identification of Rainfall Patterns Using the EOF Method

Principal Component Analysis (PCA) was applied to the rainfall data matrix in mainland Papua to simplify the complex data, identify dominant geographic and seasonal patterns, and find patterns that explain most of the rainfall variability. Marine rainfall data were excluded. PCA modes with higher variance have a greater contribution to the total variability of the data. Dominant variance of SACA&D data described in Figure 4.

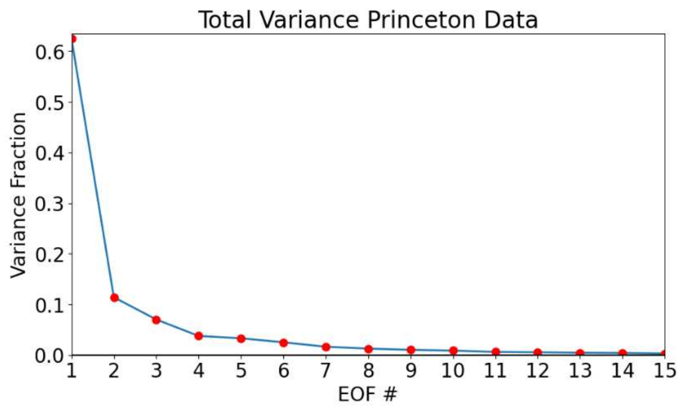
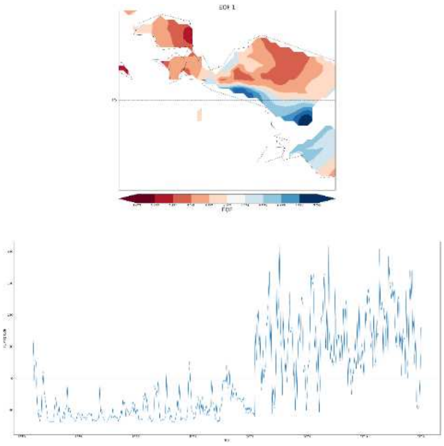


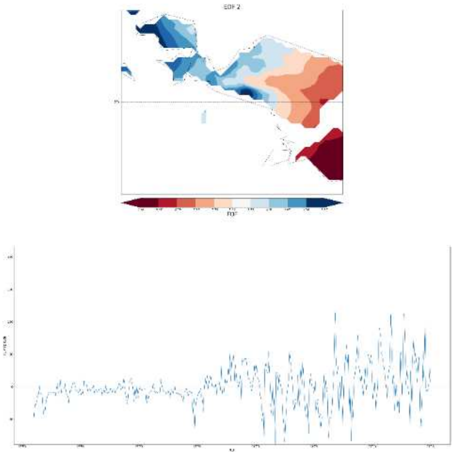
Figure 4. Dominant Variance of SACA&D Data

Figure 4 shows that the total variance is 73.93%. A larger PCA mode variance value indicates a greater contribution to the observed event. As shown by BMKG's SACA&D data, PCA components with high mode variance values have a significant impact on explaining the variation in the data.

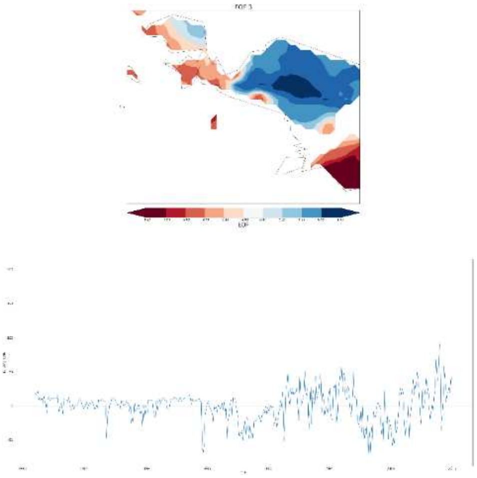
Figure 4 (a) shows the first principal mode (PC1) in the data analysis, i.e. its spatial and temporal patterns, and its contribution to the data variability. The variance of the first EOF mode, determined using the first 15 principal components, shows that this mode explains 62.53% of the data variability, making it the most dominant mode. The EOF 1 analysis shows that almost the entire Papua region experiences a positive anomaly pattern with a range of values between 1.029-8.037 mm. Figure 4 (b) (PC2) in the data analysis has a distinctive spatial and temporal pattern. The variance value of the second EOF mode shows a contribution of 11.39%. EOF2 analysis indicates that Papua dominantly experiences negative and positive anomaly patterns. The second principal component (PC2) of areas experiencing negative anomaly patterns are Papua, South Papua and Papua Mountains with a range between -0.93 to -7.56 mm. Then areas with positive anomaly patterns occur in Southwest Papua Province, West Papua, parts of Papua and Central Papua with a range from 0.72 to 9.00 mm. Figure 4 (c) (PC3) shows that the PC3 mode explains 7.01% of the data variability. EOF3 indicates that Papua dominantly experiences positive and negative anomaly patterns. Areas with positive anomaly patterns occur in Papua, Papua Mountains, Central Papua, parts of South Papua and West Papua with a range of 0.67-6.87 mm. Then areas with negative anomaly patterns occur in Southwest Papua, parts of South Papua and West Papua with a range of -0.88 to -8.62 mm.



(a)



(b)



(c)

Figure 5. Spatial Plots of the First, Second and third PCA Modes and Temporal Plots of the PCA Modes

Three main orthogonal modes (EOF1, EOF2, EOF3) account for the majority of the temporal variability of the data (80.93% of the variance of rainfall in Papua), with EOF1 being the most dominant. The unexplained variability (11.47%) is assumed to come from other variables that have little impact individually.

The EOF research in Papua using Google Colab identified three EOF modes, with the first mode explaining the largest variance, in line with previous research showing a decrease in variance contribution in subsequent modes. Such as research from Ariska, et al which resulted in three main modes, which explained 38.57% (first mode), 13.92% (second mode), and 8.93% (third mode) of the total variance with the first mode being the most dominant mode [14].

3.5 Analisis Komposit

This research examines the effects of the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), phenomena on climate and rainfall in Papua for 35 years (1981-2015), especially in the ASO and NDJ seasons. During El Niño, Papua experiences a significant decrease in rainfall in the ASO season (-3.7 mm in almost all areas), but this decrease is reduced in the NDJ season (-1.2 mm). In contrast, during La Niña, there is an increase in rainfall in almost all affected areas.

In the ASO season, rainfall increases almost all over Papua (3.0 mm), in the NDJ season, the increase in rainfall in Papua is less than in the ASO season (1.4 mm). Based on the results of the composite analysis, the classification of the influence of El Niño and La Niña phenomena on climatic conditions in Papua can be seen clearly in the table presented below (Table 2).

Table 2. Classification of the Influence of El- Nino and La Nina Phenomena on the Decrease and Increase of Rainfall in Papua

Climate Anomalies	**Region**	
	ASO Season	NDJ Season
El Niño (Decreased rainfall)	Papua Barat Daya, Papua Barat, Papua, Papua Tengah, Papua Pegunungan, Papua Selatan	Papua Barat Daya, Papua Barat, Papua, papua Tengah, Papua Selatan
La Niña (Increased rainfall)	Papua Barat Daya, Papua Barat, Papua Selatan, Papua, Papua Pegunungan	Papua Barat Daya, Papua Barat, Papua Tengah, Papua Selatan

During the positive IOD phase, most of Papua experiences decreased rainfall (negative anomalies) during the ASO and NDJ seasons, with the most pronounced impact seen in the drought-inducing ASO season (-2.6 mm). In contrast, during the negative IOD phase, most of Papua experienced increased rainfall (positive anomalies) during the ASO and NDJ seasons. In the ASO season, the increase in rainfall reached 4.0 mm. During the NDJ season, the increase in rainfall decreases to 1.7 mm but more areas experience rainfall (Table 3).

Table 3. Classification of The Influence of Positive and Negative IOD Phenomena on The Decrease And Increase of Rainfall in Papua

Climate Anomalies	**Region**	
	ASO Season	NDJ Season
IOD Positif (Decreased rainfall)	Papua Barat Daya, Papua Barat, Papua Tengah, Papua Pegunungan, Papua Selatan	Papua Barat Daya, Papua Barat, Papua Tengah, Papua, Papua Selatan
IOD Negatif (Increased rainfall)	Papua Barat Daya, Papua Barat, Papua Tengah, Papua Selatan	Papua Barat, Papua Tengah, Papua Pegunungan, Papua Selatan

Many studies have investigated the impact of ENSO and IOD on rainfall in Indonesia, for example Anggraini et al. in 2024 [15] found that El Niño and IOD are positively correlated with dry conditions in Nusa Tenggara, while La Niña and IOD are negatively correlated with wet conditions. The results of this study show that La Niña and the negative phase of the Indian Ocean Dipole (IOD) contribute to an increase in rainfall intensity in different parts of Indonesia. In contrast, El Niño and the positive phase of the IOD are associated with a decrease in rainfall in Indonesia.

4. Conclusion

The analyzed rainfall averages show that the Papua region as a whole experiences medium intensity rainfall, which ranges from 0-9 mm per month. Analysis using the Empirical Orthogonal Function (EOF) method reveals three main patterns that contribute to this rainfall variation. These modes represent different spatial and temporal patterns of rainfall anomalies. EOF1 indicates that Papua predominantly experiences positive anomalies, EOF2 and EOF3 indicate that Papua predominantly experiences negative and positive anomalies. The EOF mode identifies three main modes that explain 62.53%, 11.39% and 7.01% of the total variance, respectively. Composite analysis shows that rainfall variability in Papua is strongly influenced by the interaction of IOD and ENSO. Positive IOD and El Niño trigger dry conditions, while negative IOD and La Niña cause wet conditions.

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