MAUSAM, **77**, 2 (April 2026), 473-484

MAUSAM

DOI: https://doi.org/10.54302/mausam.v77i2.6912
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No.551.577.5(594.55)

The Impact of ENSO on rainfall changes in the northern coast of Central Java

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(*Received 4 December 2024, Accepted 8 October 2025*)

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सार – इस अध्ययन का उद्देश्य मध्य जावा के उत्तरी तटीय क्षेत्र में वर्षा की परिवर्तनशीलता पर अल नीनो-दक्षिणी दोलन (ईएनएसओ) घटना के प्रभाव का विश्लेषण करना है। यह क्षेत्र बाढ़ और सूखे जैसी जल-मौसम संबंधी आपदाओं के प्रति संवेदनशील है, जिनका स्थानीय समुदायों पर महत्वपूर्ण सामाजिक और आर्थिक प्रभाव पड़ता है। उपयोग किए गए आंकड़ों में 1994-2023 की अवधि के दौरान 22 वर्षामापी केंद्रों से प्राप्त मौसमी वर्षा के आंकड़े और महासागरीय नीनो सूचकांक (ओएनआई) के माध्यम से पहचाना गया ईएनएसओ सूचकांक शामिल है। अल नीनो, ला नीना और निष्प्रभावी वर्षों के दौरान वर्षा की विसंगतियों की सार्थकता का आकलन करने के लिए मोंटे कार्लो बूटस्ट्रैप रीसैंपलिंग विधि का प्रयोग किया गया। विश्लेषण के परिणाम बताते हैं कि अल नीनो जून-जुलाई-अगस्त (जेजेए) और सितंबर-अक्टूबर-नवंबर (एसओएन) ऋतुओं में वर्षा की कमी को काफी हद तक प्रभावित करता है, कुछ क्षेत्रों में, विशेष रूप से डेमाक और सेमारंग में, वर्षा में 70% से अधिक की कमी देखी गई है। इसके विपरीत, ला नीना से वर्षा में उल्लेखनीय वृद्धि होती है, विशेष रूप से जून-जुलाई-अगस्त (जेजेए) ऋतु में 50% से अधिक बढ़ जाती है। डीजेएफ (दिसंबर-जनवरी-फरवरी) और एमएएम (मार्च-अप्रैल-मई) ऋतुओं के दौरान, अल नीनो और ला नीना के प्रभाव अधिक भिन्न-भिन्न पैटर्न प्रदर्शित करते हैं। डीजेएफ ऋतु में, वर्षा पर अल नीनो का प्रभाव अपेक्षाकृत कम होता है, हालांकि कुछ तटीय क्षेत्रों में वर्षा में वृद्धि देखी जाती है। वहीं, इस ऋतु में ला नीना के कारण अधिकांश क्षेत्र में वर्षा में वृद्धि होती है। एमएएम ऋतु में, अल नीनो के प्रभाव से वर्षा में वृद्धि और कमी दोनों देखी जाती हैं, जो मध्य जावा के उत्तरी तटीय क्षेत्र के अधिकांश भाग में भिन्नता दर्शाती है, जबकि ला नीना का पैटर्न इसके विपरीत होता है, जिससे कई क्षेत्रों में वर्षा में कमी आती है। वर्षा के वितरण पैटर्न दो ईएनएसओ चरणों के बीच स्पष्ट स्थानिक और कालिक विभिन्नता दर्शाते हैं, जो मध्य जावा के उत्तरी तटीय क्षेत्र में आपदा न्यूनीकरण नीतियों के लिए महत्वपूर्ण निहितार्थ प्रदान करते हैं।

ABSTRACT. This study aims to analyze the influence of the El Niño-Southern Oscillation (ENSO) phenomenon on rainfall variability in the northern coastal region of Central Java. This region is vulnerable to hydrometeorological disasters, such as floods and droughts, which have significant social and economic impacts on local communities. The data used includes seasonal rainfall from 22 rain gauge stations over the period of 1994–2023, as well as the ENSO index identified through the Oceanic Niño Index (ONI). The Monte Carlo Bootstrap Resampling method was employed to assess the significance of rainfall anomalies during El Niño, La Niña, and neutral years. The analysis results indicate that El Niño significantly impacts the reduction of rainfall in the JJA (June-July-August) and SON (September-October-November) seasons, with decreases of more than 70% in some areas, especially in Demak and Semarang. In contrast, La Niña significantly increases rainfall, especially in the JJA season, with an increase of more than 50%. During the DJF (December-January-February) and MAM (March-April-May) seasons, the effects of El Niño and La Niña exhibit more varied patterns. In the DJF season, the impact of El Niño on rainfall is relatively weak, although some coastal areas show increased rainfall. Meanwhile, La Niña during this season leads to increased rainfall across most of the region. In the MAM season, the effects of El Niño show both increases and decreases in rainfall, with variations across most of northern coastal region of Central Java, while La Niña shows the opposite pattern, with reduced rainfall in several areas. The distribution patterns of rainfall reveal marked spatial and temporal variations between the two ENSO phases, providing important implications for disaster mitigation policies in the northern coastal region of Central Java.

Key words – Rainfall change, ENSO, Northern coastal Central Java, Monte Carlo Bootstrap.

1. Introduction

Central Java is one of the provinces in Indonesia that experiences a monsoon climate, characterized by a distinct difference between the rainy and dry seasons (BMKG 2022) The seasonal pattern in this region is primarily influenced by the Asian and Australian monsoon systems. Additionally, inter-annual climate variability, such as the El Niño-Southern Oscillation (ENSO) (Ahn et al. 2020) and the Dipole Mode (DM) (Li *et al.*, 2015), also significantly affects rainfall fluctuations and weather conditions in the region. ENSO refers to the phenomenon of alternating phases between El Niño, characterized by warmer-than-average sea surface temperatures (SST) in the central and eastern tropical Pacific, and La Niña, which is the opposite phase (Hidayat *et al.*, 2022). ENSO influences climate change on global, regional, and local scales, including in coastal areas of Indonesia (Setiawan *et al*., 2017). Moreover, ENSO also impacts sea level anomalies, which can increase significantly during certain ENSO events (Fadhlan *et al*., 2017). Many studies have found that most hydrometeorological disasters, such as droughts or heavy rainfall events, are linked to the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (Fadholi *et al*. 2013; Kasihairani *et al*., 2014; Lestari *et al*., 2018; Mulyana 2002; Prasetyo *et al*., 2018; Sekaranom *et al*., 2020; Yuggotomo and Ihwan 2014).

Central Java is one of the regions most vulnerable to natural disasters, especially hydrometeorological disasters (Endah Larasasti, 2023). This is consistent with the report by BNPB (2016), which indicates that the trend of disasters has been continuously increasing in Indonesia. The year 2016 recorded the highest number of disasters in the past decade, with a 35% increase compared to 2015. In 2016, there were 2,342 disasters, 92% of which were dominated by floods, landslides, and tornadoes. The increase in hydrometeorological disasters is generally caused by high rainfall in the region. Additionally, reduced rainfall can lead to droughts and decreased water availability in Java (BAPPENAS, 2011). Studies show that annual air temperature in Java has been increasing over the past 30 years, and there is a negative correlation between air temperature and humidity as well as rainfall intensity, meaning that rising temperatures tend to be followed by decreasing humidity and rainfall (Prasetyo *et al*., 2021).

Previous research has investigated the impact of the El Niño-Southern Oscillation (ENSO) on rainfall in Central Java. Malinda Hidayat *et al*. (2018) conducted a study on the influence of ENSO on rainfall in the Semarang region, and the results showed a significant relationship between the Nino 3.4 index and the Southern Oscillation Index (SOI) with rainfall variation, especially during the transition season of September-October-November (SON). Then, Asyam Andi *et al*. (2024) examined the impact of ENSO and the Indian Ocean Dipole (IOD) on sea surface temperature and rainfall in the southern coast of Central Java. The results showed that during El Niño and positive IOD events, sea surface temperatures cooled and rainfall decreased significantly, while during La Niña and negative IOD events, sea surface temperatures warmed and rainfall increased. Furthermore, a study by Yustiana *et al*. (2023) identified the impact of ENSO on rainfall and sea level anomalies along the northern coast of Central Java, but it focused only on a few cities, namely Brebes, Pemalang, Pekalongan, and Semarang. The results indicated that rainfall anomalies often correlate with sea level variations during certain seasons. However, these studies tended to focus on the local impacts of ENSO without providing a detailed analysis of spatial and temporal variability across the entire northern coast of Central Java.

This study will focus on the impact of ENSO on rainfall changes along the northern coast of Central Java. This analysis is important as the coastal areas of Central Java face threats such as abrasion and frequently experience flooding and tidal inundation due to heavy rainfall and rising sea levels, which have significant social and economic impacts on the local communities (Maulana *et al*., 2017). Additionally, the northern coastal region of Central Java has significant development potential due to its rich natural resources, both biological and non-biological, as well as its strategic position for regional development in various sectors (Ekosafitri *et al*., 2017). This study employed the Monte Carlo Bootstrapping method, a resampling technique that assumes the sample data represent the population. This method was used to assess the significance or influence of ENSO on rainfall anomalies (Curtis *et al*., 2007; Li *et al*., 2011; Tangang *et al*., 2017). The advantages of this method include its ease of application to various types of statistics, higher accuracy compared to other methods, and fewer assumptions, as it does not require normal distribution or large sample sizes (Nugroho *et al*., 2024). By understanding how rainfall patterns change according to ENSO phases, it is hoped that this research can provide a foundation for disaster mitigation policy-making in the northern coastal areas of Central Java.

2. Data and methodology

2.1. *Study Area*

This research was conducted in cities and regencies along the northern coast of Central Java, including Brebes, Tegal City, Tegal Regency, Pemalang, Pekalongan City,

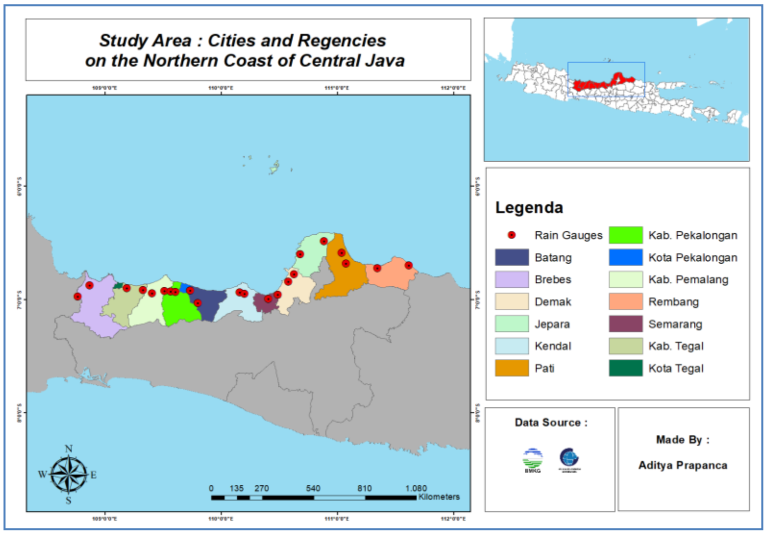


Fig. 1.Map of the Study Area

Pekalongan Regency, Batang, Kendal, Semarang City, Demak, Jepara, Pati, and Rembang. The northern coastal region of Central Java is located at coordinates 6°30'–7°00' S and 108°30'–111°30' E.

2.2. *Data*

The data used in this study include the Oceanic Niño Index (ONI) and monthly rainfall data from 1994 to 2023. The list of ENSO years, as shown in Table 1, was determined based on the ONI index from the Climate Prediction Center (CPC) of NCEP NOAA (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), calculated using a three-month moving average of reconstructed sea surface temperature anomalies in the Niño 3.4 region (5° N–5° S, 120°–170° W). El Niño (La Niña) is defined when the ONI value reaches at least +0.5 °C (−0.5 °C). As shown in Table 1, ENSO years may vary by season, depending on the ONI index values. Periods not identified as El Niño or La Niña years are classified as neutral years.

Daily rainfall data were obtained from 22 rainfall observation posts operated by the Meteorology, Climatology, and Geophysics Agency (BMKG) distributed along the northern coast of Java. The selection of rainfall posts was based on those with the longest data series in each city or regency near the northern coast of Central Java. However, some rainfall posts had missing data, which were filled using the mean imputation method to address gaps. These observation stations include Kubang, Cibendung, Kemantren, Warurejo, Karang Tengah, Sungapan, Sragi 1, Wiradesa, Bandar, Dracik Kramat, Babadan, Trompo, Karangroto, Simongan, Bungo, Jatirogo, Beji/BPP Kalingga, Jepara, Ngemplak

TABLE 1

El Niño or La Niña years during the period 1994-2023 based on ONI Index

Phase	Season	Years
El Niño	JJA	1997, 2002, 2004, 2009, 2015,2023
	SON	1994, 1997, 2002, 2004, 2006, 2009, 2014, 2015, 2018, 2023
	DJF	1994/95, 1997/98, 2002/03, 2004/05, 2009/10, 2015/2016, 2018/19, 2023/24
	MAM	1998, 2003, 2015, 2016, 2019
La Niña	JJA	1998, 1999, 2000, 2007, 2010, 2011, 2022
	SON	1995, 1998, 1999, 2000, 2007, 2010, 2011, 2016, 2017, 2020, 2021, 2022
	DJF	1995/96, 1998/99, 1999/00, 2000/01, 2007/08, 2010/11, 2011/12, 2020/21, 2021/22
	MAM	1999, 2000, 2008, 2011, 2012, 2021, 2022

Lor, Trangkil, Kragan, and Rembang/Turusgede. Subsequently, the monthly rainfall data were processed into seasonal data for each year.

To construct seasonal composites of the Walker circulation, monthly data of zonal wind (u; m/s) and vertical velocity (ω; 10^{-2} Pa/s) at the 1000-100 hPa levels from 1948 to 2024 were used. These data were downloaded from https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html. However, we selected only the ENSO years based on Table 1 to generate the seasonal composites of the Walker circulation for both El Niño and La Niña phases.

2.3. *Method*

The process begins by grouping monthly rainfall data from rain gauge stations into seasonal data with the format DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), and SON (September-October-November). Subsequently, ENSO years are identified based on the El Niño category (marked in red), La Niña category (marked in blue), and normal years (unmarked).

The seasonal rainfall data is then categorized into three groups based on ENSO years: El Niño, La Niña, and normal years. Resampling is conducted solely on seasonal data from normal years. The average seasonal rainfall from normal years is further analyzed using the Monte Carlo Bootstrap resampling method to generate 1000 samples. This process is performed using the following mathematical formula (Nugroho *et al*., 2024) :

$$X^* = (X^*_1, X^*_2, X^*_3, \ldots, X^*_n) \quad (1)$$

where X represents the initial sample data to be used for generating bootstrap samples, denoted as X^*, by performing resampling with replacement n times (n=1000). Subsequently, statistical calculations are performed for each bootstrap sample. This involves applying a statistical function TT to the bootstrap samples, which is denoted as (T*).

$$T^* = T(X^*) \quad (2)$$

where T represents the statistical function applied to the sample data. In this case, T is the mean, T* represents the average value of each bootstrap sample. From the 1000 mean values obtained, the upper and lower bounds are calculated based on the 5^{th} and 95^{th} percentiles. If the mean rainfall during ENSO years lies outside these bounds, the impact of ENSO is considered significant.

For seasonal rainfall data during El Niño and La Niña years, only the average rainfall values (DJF, MAM, JJA, SON) are calculated. Meanwhile, the average seasonal rainfall for normal years after resampling is used to compute the lower and upper percentiles using Excel formulas with a significance level (α) of 5%.

The hypothesis testing is carried out as follows:

(*i*) H0 accepted: If the mean value falls within the range of the lower and upper percentiles, the ENSO impact is considered insignificant, and the region is deemed unaffected.

(*ii*) H1 accepted: If the mean value lies outside the range of the lower and upper percentiles, the ENSO impact is considered significant, and the region is deemed affected (H0 rejected).

If H0 is accepted, it implies that rainfall during ENSO years is similar to rainfall during normal years, indicating that the ENSO impact is insignificant. However, if H1 is accepted and H0 is rejected, the degree of ENSO impact is calculated using rainfall anomaly values. The impact of ENSO on rainfall changes is determined using Equation 3.

$$\%\text{Anomaly} = \frac{X_{Enso} - X_{neutral}}{X_{neutral}} \text{x}100\% \quad (3)$$

where X_{enso} represents the average rainfall during ENSO years, and X_{netral} represents the average rainfall during normal years (Supari *et al*., 2018). The impact values are then classified into four categories: <20%, 20–50%, and >50%. The data processing in this study is conducted using Microsoft Excel and RStudio. The resulting impact levels are then mapped using ArcGIS 10.8 software to create maps illustrating the influence of El Niño and La Niña on rainfall changes in the northern coastal regions of Java Island.

3. Results and discussions

3.1. *Descriptive statistics and seasonal rainfall variability on the Northern coast of java*

Based on the statistical analysis of rainfall at 22 observation stations (Table 2), a seasonal pattern consistent with the monsoonal climate characteristics of Java is observed, with the highest rainfall occurring in the DJF season (December–February) and the lowest in the JJA season (June–August). The highest standard deviation is also recorded in the DJF season, indicating large interannual rainfall variability, while the lowest standard deviation is found in the JJA season. The greater variability during the transitional seasons (MAM and SON) suggests the possible influence of the combined effects of ENSO and IOD, which enhance rainfall fluctuations.

The rainfall variability occurring in Java is closely related to the ENSO phenomenon. The study by Nur'utami and Hidayat (2016) shows that rainfall in Indonesia, particularly in Java, is strongly influenced by atmosphere ocean interactions in the Indo Pacific region. The El Niño phenomenon tends to cause cooler sea surface temperature (SST) anomalies around Indonesia, weakening the Walker Circulation and significantly triggering a decrease in rainfall.

In addition, this is supported by the findings of Hamada *et al*. (2012), who specifically investigated interannual rainfall variability in northwestern West Java. They found that during the dry season (May–October),

TABLE 2

Mean values and standard deviations of seasonal rainfall from 22 rainfall stations on the north coast of Java Island

Observation Station	MAM		JJA		SON		DJF	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
Dracik Kramat	182	68,0	66	55,5	95	64,5	409	154,3
Bandar	280	100,3	79	55,0	185	106,8	593	223,2
Kubang	178	60,8	37	33,9	76	60,5	289	83,7
Cibendung	241	67,4	49	42,5	120	69,2	345	85,4
Bungo	162	61,1	24	25,7	102	62,4	472	117,9
Jatirogo	153	62,7	32	39,7	93	52,9	352	136,9
Jepara	138	53,9	26	23,4	83	54,1	456	136,6
Beji/Bpp Kalingga	171	66,8	44	34,6	90	54,9	540	177,9
Babadan	156	66,9	49	47,0	107	72,1	337	115,7
Trompo	151	46,2	54	51,7	107	66,9	326	99,5
Trangkil	145	57,8	51	48,7	83	60,0	261	74,2
Ngemplak Lor	184	56,6	63	50,2	101	58,8	338	109,4
Sragi 1	167	60,5	53	49,6	90	67,1	376	149,9
Wiradesa	156	88,9	39	37,1	76	66,0	336	132,4
Sungapan	181	57,4	49	43,0	102	65,3	381	96,2
Karang Tengah	198	157,2	49	35,6	99	73,2	426	163,6
Kragan	130	37,5	49	40,2	79	56,3	185	67,4
Rembang / Turusgede	143	52,6	41	37,1	90	54,8	285	102,8
Karangroto	180	44,2	58	52,7	140	81,6	345	82,8
Simongan	190	67,5	66	48,6	166	95,9	350	102,8
Warurejo	166	62,9	45	40,0	76	60,1	323	92,5
Kemantren	161	47,8	45	40,0	73	55,1	315	62,3

droughts in this region often occur when El Niño coincides with a positive IOD event. Under such conditions, sea surface temperatures around Indonesia become cooler, leading to atmospheric divergence and reduced atmospheric moisture content, thereby suppressing convection processes and decreasing rainfall.

The graph above shows the interannual variability of rainfall during the period 1994–2023 in the northern coastal region of Java, based on seasonal averages from 22 observation stations. The seasonal rainfall graph for the northern coast of Java clearly displays a consistent monsoonal pattern, where the December-February (DJF) season is the peak of the wet season with the highest precipitation, while the June-August (JJA) season is the peak of the dry season. Specifically, the La Nina phase is associated with periods of above average rainfall, indicating a wetter wet season. Conversely, the El Nino phase is closely linked to periods of below-average rainfall, signifying drier or drought conditions. In strong El Niño years, such as 1997/1998, rainfall decreases sharply especially during JJA and SON, also the graph shows a very sharp decrease in DJF rainfall, making it one of the lowest on record. This directly illustrates the suppressive impact of El Nino on precipitation. In contrast, during the La Nina episode of 2020/2021, there was a significant spike in DJF rainfall, which also registered as one of the highest peaks in the dataset. These fluctuations indicate that the interannual variability of rainfall in this region is strongly influenced by the combined effects of ENSO and IOD. When El Nino coincides with a positive IOD, there is a significant reduction in rainfall during the dry and transitional seasons, while La Nina accompanied by a negative IOD leads to increased rainfall.

3.2. *The influence of ENSO on changes in rainfall on the north coast of Java Island*

The ENSO (El Niño-Southern Oscillation) phenomenon typically lasts for two consecutive years, with the first year referred to as the development year (designated as year '0') and the second year as the decay year (designated as year '1') (Supari *et al*., 2018). Most

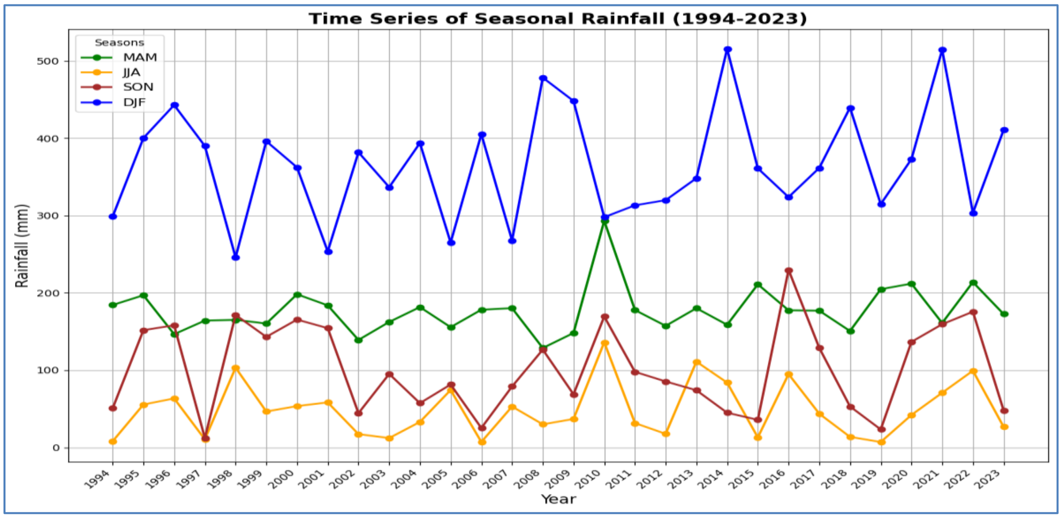
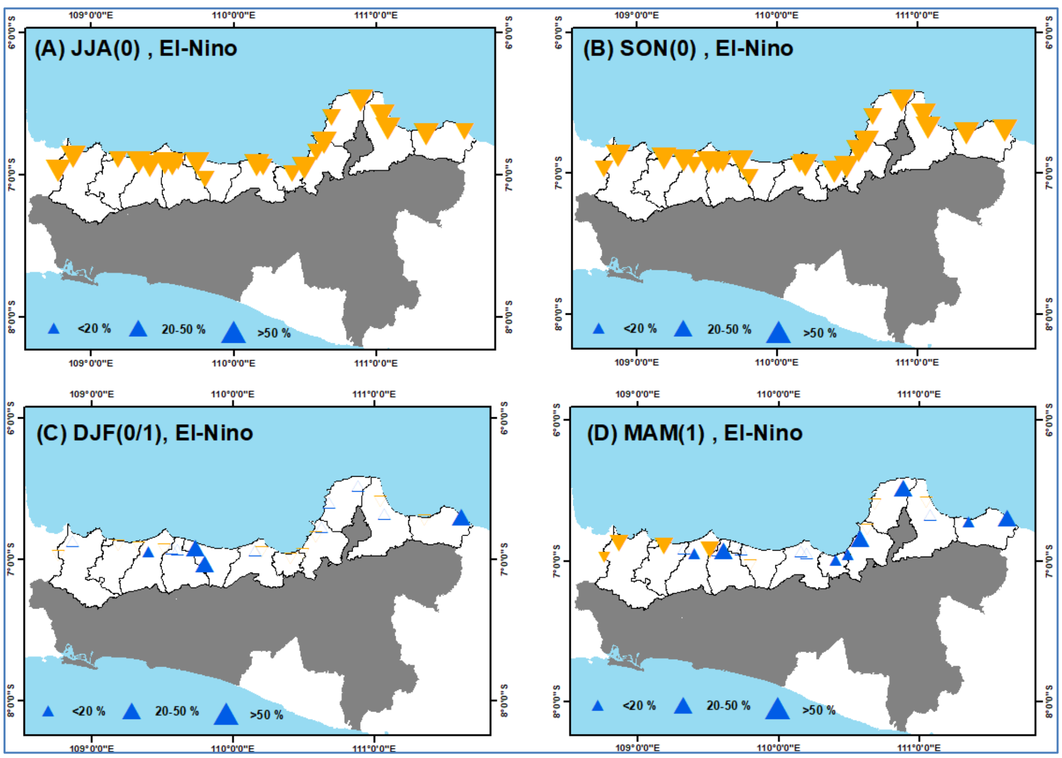
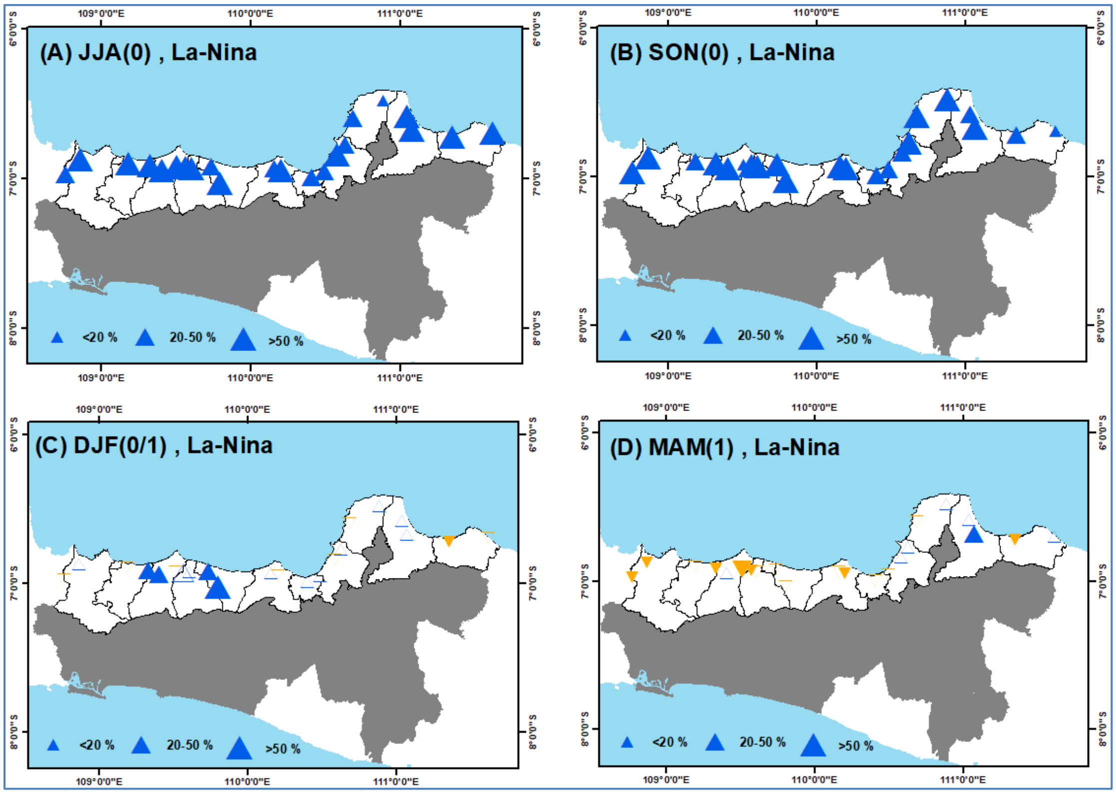


Fig. 2. Interannual rainfall variability based on seasonal averages at 22 rain gauge stations in the northern coastal region of Java for the period 1994–2023



Figs. 3(a-d). The impact of El Niño on rainfall changes is analyzed for the DJF (a), MAM (b), JJA (c), and SON (d) seasons. Upward-facing blue triangles indicate an increase in rainfall, while downward-facing orange triangles indicate a decrease. Filled triangles represent significant anomalies at the 95% confidence level.

ENSO events begin between March and September of the development year and end around February–March of the decay year (Trenberth, 1997). To maintain consistency, this study interprets the periods JJA(0) and SON(0) as the development year, DJF(0/1) as the transition from the end of the development year to the beginning of the decay year, and MAM(1) as the decay year. As an example, during the 1997/1998 El Niño event, the analyzed seasons included JJA of 1997, SON of 1997, DJF spanning 1997/1998, and MAM of 1998.



Figs. 4(a-d). The impact of La Niña on rainfall changes is analyzed for the DJF (a), MAM (b), JJA (c), and SON (d) seasons. Upward-facing blue triangles indicate an increase in rainfall, while downward-facing orange triangles indicate a decrease. Filled triangles represent significant anomalies at the 95% confidence level.

During the DJF and MAM seasons, the reduction in rainfall (dry conditions) caused by El Niño tends to be less intense as ENSO reaches its peak and decay phases in the northern coastal regions of Central Java (Figs. 3C & 3D). In these seasons, rainfall changes are highly variable, with dry conditions not being more dominant than wet conditions. During DJF and MAM, most of the northern coastal areas of Central Java experience increased rainfall (wet conditions) during El Niño years. However, some areas still show dry conditions, particularly in Tegal, Semarang, Demak, parts of Pati, and parts of Rembang during DJF. Dry conditions are also observed in Brebes, Tegal City, parts of Demak, and parts of Jepara during MAM. The rainfall anomaly patterns between DJF and MAM in the northern coastal regions of Central Java exhibit opposite trends, possibly due to local influences such as topography and diurnal cycles in the area (Qian *et al.*, 2010).

During the DJF season, the impact of El Niño on rainfall in the northern coastal regions of Central Java is predominantly insignificant. This aligns with findings by Hendon (2003) and Haylock (2001), which suggest that ENSO's influence on Indonesian rainfall during DJF is generally weak. However, in contrast, during the MAM season, most of the northern coastal regions of Central Java experience significant rainfall increases due to El Niño, with an impact level of 20–50% higher compared to neutral years.

Conversely, during the JJA season of El Niño years, a significant reduction in rainfall (marked by filled triangles) is statistically observed in all rainfall stations in the northern coastal regions of Central Java, indicating a strong El Niño effect (Fig. 3A). All rainfall stations recorded reductions between 20% and over 50% compared to neutral years. The areas of Demak and Semarang show the most severe impact, with rainfall stations recording reductions of over 70%. In the SON season, these dry conditions persist in the northern coastal regions of Central Java. The spatial distribution of affected rainfall stations and the degree of rainfall reduction remain consistent, showing a pattern very similar to that in JJA (Fig. 3B). Areas affected by El Niño with rainfall reductions of over 70% include Brebes and Rembang.

La Niña begins with the weakening of El Niño, driving the movement of warm seawater masses westward towards Indonesia. This warm temperature creates a low-

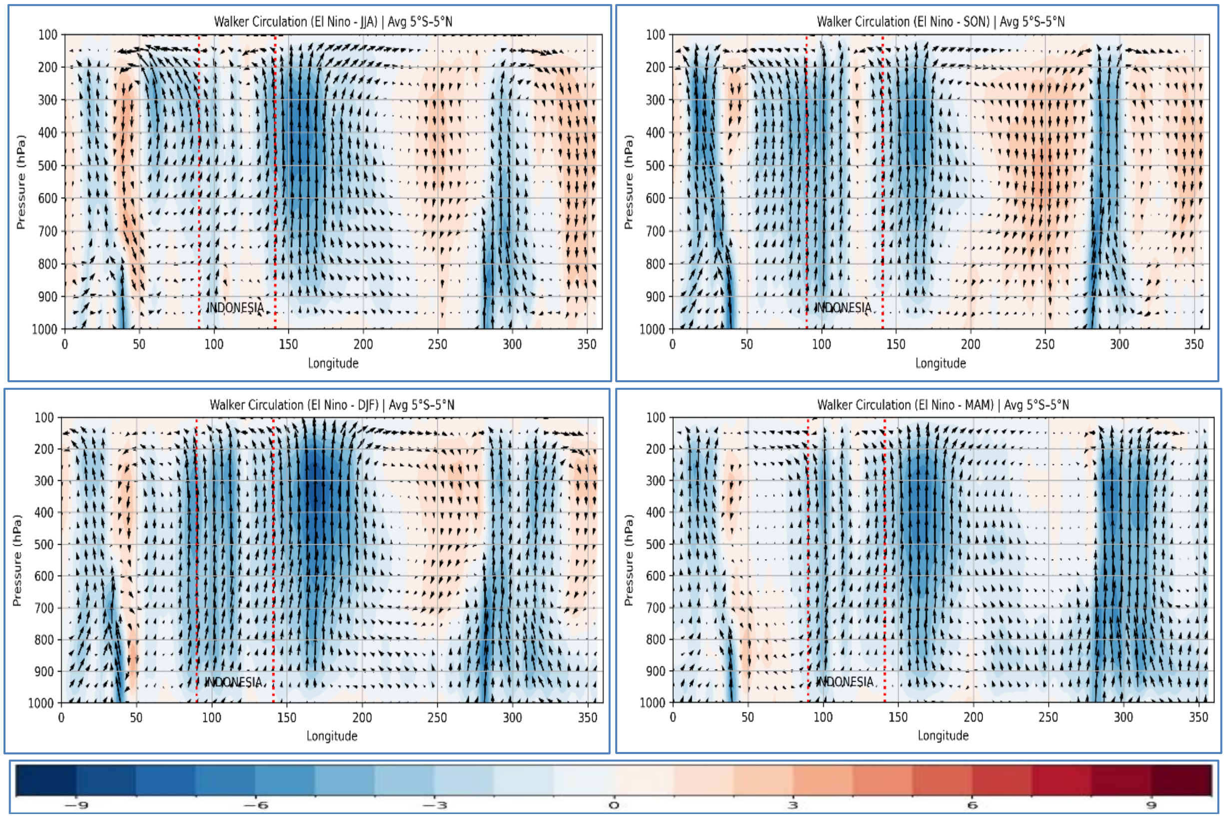


Fig. 5. Composite seasonal Walker circulation using zonal wind (u; m/s) and vertical velocity (ω; 10^{-2}Pa/s) level 1000-100 hPa during El Niño

pressure area in Indonesia, prompting winds from the South Pacific Ocean and the Indian Ocean to move into the region. These winds carry significant amounts of water vapor, leading to heavy rainfall across various parts of Indonesia (Safitri 2015).

In general, the influence of La Niña on rainfall in Indonesia is opposite to that of El Niño (Fig. 4). However, several key differences should be noted. During the JJA and SON seasons in La Niña years, the entire northern coastal region of Central Java experiences wet conditions, with a severity comparable to El Niño's impact but in the opposite pattern (Fig. 3C). All rainfall stations in these regions record significant wet anomalies, with rainfall increases of over 50% compared to neutral years. During JJA, the areas most affected by La Niña are Tegal, Pekalongan, and Demak, where rainfall stations recorded increases of over 100% compared to neutral years. However, the impact pattern of La Niña during SON shows significant differences compared to El Niño (Fig. 3B).

During the DJF season, most of the northern coastal areas of Central Java continue to experience wet conditions, marked by rainfall increases of 20–50%. Areas significantly influenced by La Niña include Tegal, Pemalang, and Batang (Fig. 4C). However, dry anomalies are still observed in certain areas, with some rainfall stations in Brebes, Kendal, Demak, Jepara, and Rembang recording rainfall reductions, though not statistically significant. This occurrence during DJF is noteworthy, given the common perception that La Niña events are typically associated with wet anomalies in Indonesia.

In contrast to DJF, dry conditions become more pronounced and dominant in the northern coastal areas of Central Java during the SON season. Most rainfall stations that previously experienced wet conditions during DJF now record significant dry conditions in the western part of the northern coast of Central Java. This phenomenon occurs because the MAM period serves as a transitional phase from the wet season to the dry season, which is associated with decreased rainfall during this phase.

3.3. *Walker circulation and zonal wind during ENSO*

The vertical wind profile, also known as the Walker circulation, refers to atmospheric circulation that arises due to the presence of a sea surface temperature (SST) gradient along the equator. The characteristics of this circulation are shaped by ocean-atmosphere interactions

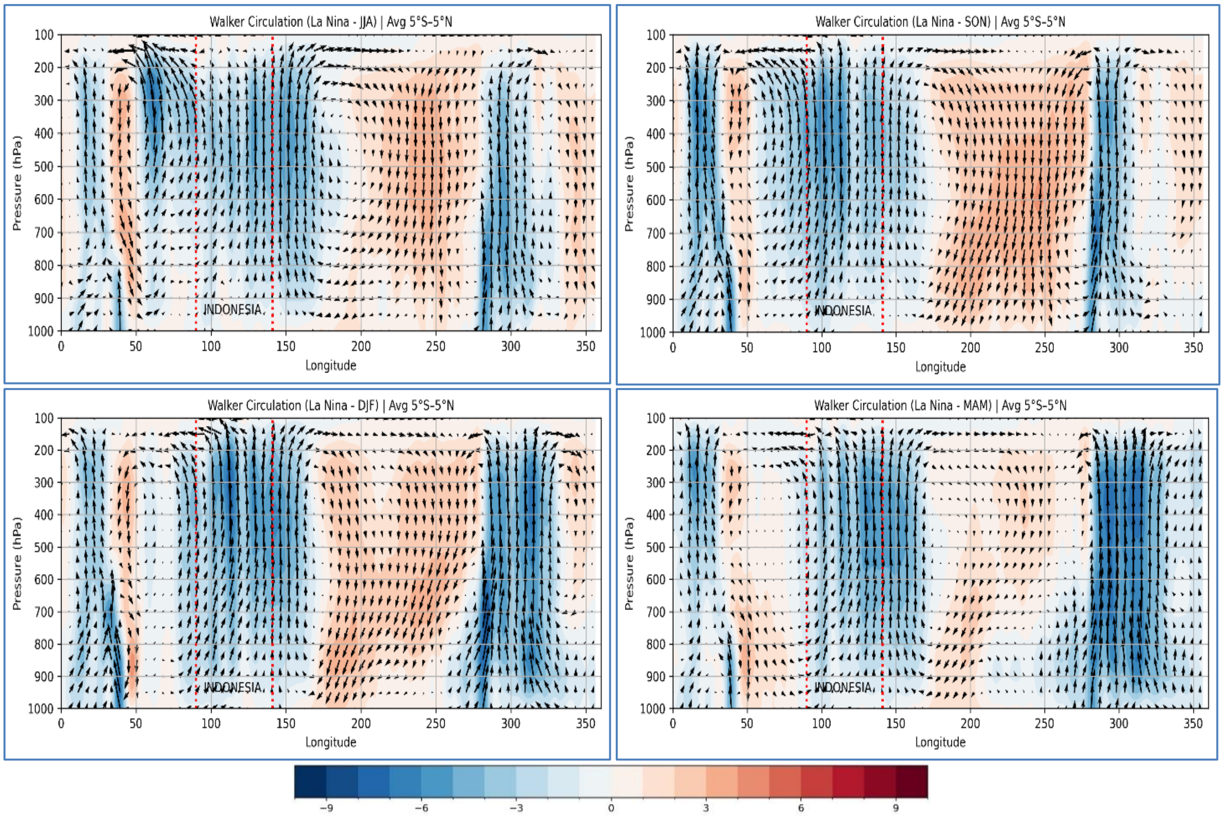


Fig. 6. Composite seasonal Walker circulation using zonal wind (u; m/s) and vertical velocity (ω; 10-2Pa/s) level 1000-100 hPa during La Niña.

within tropical regions. Walker circulation typically develops over the Pacific Ocean, with its strongest manifestation occurring in the upper levels of the atmosphere (between 300 and 200 hPa) (Lau and S.Yang 2002). The intensification of this circulation is closely associated with the cooling and warming of SSTs in the Pacific region (Lau and S.Yang 2002).

This circulation pattern can be examined using average zonal wind vectors and vertical velocity contours within the 5° N – 5° S latitude band and between the 1000 and 100 hPa pressure levels. Figure 5 illustrates composite anomalies of the Walker circulation during El Niño event. Negative values of vertical velocity indicate convective activity, while positive values represent subsidence, or descending air motion.

Based on Fig. 5, particularly during the JJA and SON seasons, parts of Indonesia (longitude 100°–150°) experience downdrafts, indicated by positive vertical velocity (reddish colors) extending from the lower to the upper atmosphere (1000–100 hPa). This condition reflects a stable and dry atmosphere, which is less favorable for the formation of convective clouds.

The presence of these downdrafts also weakens the typical updraft circulation that usually occurs over Indonesia under normal conditions, consequently shifting the convective center eastward toward the central to eastern Pacific. As a result, during the JJA and SON seasons in El Niño phases, significant reductions in rainfall occur across Indonesia, including Java Island. In contrast, during the DJF and MAM seasons, when the El Niño phase begins to weaken, Indonesia is predominantly influenced by strong updrafts.

During La Niña events, the Walker circulation over the equatorial region intensifies, characterized by strong easterly zonal winds at the surface and robust updrafts over the Maritime Continent, including Indonesia. The seasonal composites from 1994 to 2023 show consistent updrafts (indicated by negative vertical velocity and blue shading) between 100° E and 130° E throughout all seasons (JJA, SON, DJF, and MAM). These upward airflows are part of an enhanced convective branch of the Walker circulation, which is sustained by warmer than average sea surface temperatures in the western Pacific. In the upper troposphere, westward return flow completes the circulation loop, further strengthening large-scale convection over Indonesia and surrounding regions.

This intensification of the Walker circulation enhances moisture convergence and the vertical development of convective clouds over the Indonesian region, leading to significantly increased seasonal rainfall. The strong updrafts during DJF and MAM support the observed wet anomalies across most parts of northern Central Java, as reflected in the rainfall station analysis. In JJA and SON, the continued presence of deep convection suggests that La Niña sustains wet conditions even during typically dry periods. These dynamics underscore the critical role of vertical and zonal atmospheric circulations in modulating rainfall distribution during La Niña, reaffirming Indonesia's sensitivity to equatorial Pacific variability.

Ratna *et al.*, 2017 conducted a study using the WRF regional climate model to assess the climatology and interannual variability of rainfall over Southeast Asia. Their results demonstrate that the model effectively reproduces anomalies in 850 hPa zonal wind and vertical atmospheric circulation linked to ENSO and Indian Ocean Dipole (IOD) phases, which influence rainfall patterns across Indonesia, including Java. During El Niño events, the weakening of the Walker circulation is associated with enhanced downdrafts over the region, leading to suppressed convection and decreased rainfall, particularly during boreal summer (JJA) and autumn (SON).

Conversely, during La Niña phases, an intensification of the Walker circulation and updrafts promotes enhanced convective activity and increased precipitation. These findings support the understanding that Walker circulation dynamics and zonal wind anomalies are critical mechanisms modulating ENSO's impact on regional rainfall variability. Furthermore, they underscore the importance of considering the interaction between ENSO and IOD when analyzing the spatial and temporal patterns of rainfall in the Indonesian region.

4. Conclusions

This study demonstrates that the El Niño-Southern Oscillation (ENSO) phenomenon has a significant impact on changes in rainfall patterns along the northern coast of Central Java, both during the El Niño and La Niña phases. During the El Niño phase, particularly in the JJA (June, July, August) and SON (September, October, November) seasons, a significant reduction in rainfall is observed in most areas of the northern coast of Central Java, with some regions such as Semarang and Demak experiencing a decrease of more than 70%. In contrast, during the MAM (March, April, May) and DJF (December, January, February) seasons, the influence of El Niño is more variable, with most areas experiencing an increase in rainfall. This indicates the complexity of rainfall patterns influenced by ENSO, with fluctuations that are further impacted by local factors such as topography and daily cycles.

Conversely, the La Niña phenomenon exerts the opposite effect to El Niño, with most areas along the northern coast of Central Java experiencing increased rainfall, particularly in the JJA and SON seasons. In these seasons, regions such as Tegal and Pekalongan recorded an increase in rainfall of more than 100% compared to neutral years. However, during the DJF season, some areas still experienced a decrease in rainfall, despite La Niña generally being associated with wet conditions in Indonesia. This study underscores the importance of understanding the spatial and temporal variability of rainfall patterns influenced by ENSO in the northern coastal region of Central Java, which can serve as a foundation for disaster mitigation policies and natural resource management planning in the area.

Authors' contributions

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