The Influence of Cross Equatorial Northerly Surge (CENS) and El Niño Southern Oscillation (ENSO) on Atmospheric Dynamics in Western Indonesia

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Abstract: Indonesia's position between the Asian and Australian continents makes its weather highly sensitive to atmospheric interactions from both regions. This study examines the impact of *Cross-Equatorial Northerly Surge* (CENS) and *El Niño Southern Oscillation* (ENSO) phasesNeutral, La Niña, and El Niñoon atmospheric dynamics over western Indonesia. The analysis focuses on CENS propagation from the southern South China Sea to the west of the Java Sea, comparing atmospheric responses during CENS-ENSO Neutral, CENS-La Niña, and CENS-El Niño events. Using ERA-5 reanalysis data and CMORPH precipitation data (0.25° spatial, hourly temporal resolution), we analyzed *sea surface temperature* (SST), *outgoing longwave radiation* (OLR), precipitation, moisture transport, and divergence. Under neutral ENSO conditions, CENS strengthens the Asian monsoon, enhancing moisture transport and convergence over northern Java, leading to increased deep con-vection and precipitation, while Sumatra and Kalimantan experience moisture divergence and reduced cloud cover. During La Niña, enhanced moisture transport and convergence extend to Kalimantan, further amplifying convective activity and rainfall. In contrast, during El Niño, the cooling effect of CENS on the South China Sea weakens, but moisture convergence intensifies over the Java Sea, triggering cloud development despite suppressed convection. These findings highlight the crucial role of CENS-ENSO interactions in modulating regional weather patterns and extreme events, offering insights for improving weather forecasting, disaster mit-igation, and climate modeling in western Indonesia.

Keywords: CENS; Divergence; ENSO; Low-level Moisture Transport; OLR; Rainfall

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I. INTRODUCTION

Indonesia is geographically located between the Asian and Australian continents, making its weather and climate significantly influenced by the atmospheric conditions of both continents. The differences in solar radiation received between high-latitude regions and the equator create pressure gradients, causing airflows from high-pressure areas to low-pressure areas. This phenomenon acts as one of the key climate-controlling factors in Indonesia, as it induces periodic changes in wind patterns, leading to seasonal variations across parts of the country [1].

From October to March, Indonesia, particularly in the western part, is influenced by the Asian Monsoon or the Boreal Winter Monsoon. This monsoon occurs due to the pressure difference between the cooling Asian landmass and the relatively warmer Indian Ocean. Cold and dry air from the Asian highlands moves southward, passing over the warm waters of the South China Sea and the Indian Ocean, thus carrying significant amounts of water vapor [2, 3]. This air mass movement triggers an increase in the formation of convective clouds across most of western Indonesia. This process reflects the characteristics of a strong seasonal wind circulation, where the airflow from the Northern Hemisphere to the Southern Hemisphere plays a crucial role in influencing regional weather patterns, including the intensity of rainfall [1].

The airflow from the Northern Hemisphere crossing the equator is referred to as cross-equatorial flow. According to previous studies, this cross-equatorial flow is characterized by dominant northerly winds near the equator and is often known as the *Cross Equatorial Northerly Surge* (CENS) [4]. CENS is a synoptic disturbance that occurs during the boreal winter season (November to March) and enhances convective activity and rainfall in the Maritime Continent of Indonesia, including western Indonesia [5]. CENS is defined as the spatially averaged northerly wind exceeding 5 m/s within the region of 105°E - 115°E and 5°S - 0° [4]. Due to the Coriolis force, the cross-equatorial flow in the Southern Hemisphere, particularly over the Java Sea, exhibits dominant northwesterly to westerly wind directions [6]. CENS events are associated with increased moisture transport and convergence, which trigger the formation of convective clouds and enhance rainfall, particularly along the northern coast of West Java [5]. Additionally, CENS influences the daily cycle of convection and moisture convergence, which, in general, can suppress convection but increase moisture accumulation in the atmosphere [7]. Furthermore, CENS is one of the contributing factors to the flooding in Jakarta on February 1825, 2020 [8].

Another climatic factor affecting Indonesia is the *El Niño-Southern Oscillation* (ENSO), which recurs every 4 to 7 years [9]. ENSO is a global climate phenomenon characterized by the warming (El Niño) or cooling (La Niña) of sea surface temperatures in the central and eastern equatorial Pacific [9]. ENSO affects global climate variability, including precipitation and temperature patterns in tropical regions [10]. ENSO modulates atmospheric dynamics through changes in sea surface temperatures that alter atmospheric circulation patterns, such as the increased variability of upper tropospheric Kelvin waves during El Niño events [11]. Additionally, ENSO also influences the winter climate of East Asia and the North Atlantic Oscillation (NAO) through complex teleconnections [12, 13]. Additionally, rainfall variability in Indonesia, particularly on Java Island, is closely related to the ENSO phenomenon [14 - 16]. During ENSO periods, high moisture variability occurred during La Niña events, with abundant moisture distributed over the Maritime Continent [17]. While during El Niño, the moisture content over the Maritime Continent decreases, resulting in below-average rainfall [18].

However, the interaction between CENS and ENSO in influencing atmospheric dynamics in western Indonesia remains uncertain. CENS events are known to enhance moisture convergence and rainfall, but these effects can be modulated by ENSO through its influence on sea surface temperatures and atmospheric circulation patterns [5], [7], [19]. For instance, during the La Niña phase, the increased moisture due to the warming of sea surface temperatures in the Indonesian region can amplify the impact of CENS on extreme rainfall. Conversely, during El Niño, the reduction of moisture in the atmosphere may weaken the effects of CENS, even though wind patterns remain active.

An unresolved issue is how the combination of CENS and ENSO specifically affects moisture transport, precipitation patterns, and atmospheric dynamics in western Indonesia. This study aims to fill this gap by analyzing the impacts of these two phenomena on atmospheric dynamic parameters, including OLR, SST, rainfall anomalies, moisture transport, and divergence, under Neutral, La Niña, and El Niño conditions. The analysis will compare atmospheric variability during CENS-ENSO Neutral, CENS-La Niña, and CENS-El Niño conditions. The primary focus of the analysis will be on the CENS propagation region, from the southern South China Sea to the western Java Sea. Thus, the results of this study are expected to provide a deeper understanding of the dominant factors between CENS and ENSO in influencing atmospheric dynamics related to the enhancement or weakening of rainfall in parts of Indonesia.

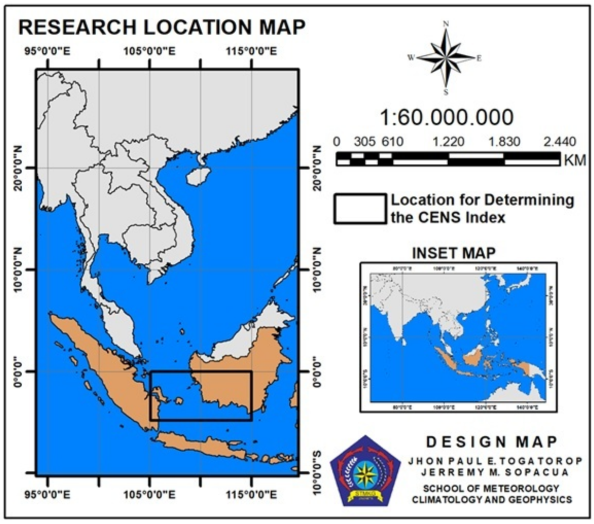

FIG. 1: Map of the study area in the western region of Indonesia.

II. METODOLOGI

A. Location and Time of the Study

The location of this study is the western region of Indonesia, with coordinates 30°N 10°S and 95°E 120°E (Fig. 1). The reason for selecting this area is because the CENS phenomenon generally passes through the South China Sea, eastern Sumatra, western Kalimantan, and the waters of Java. These areas are the main pathways of CENS, which influence atmospheric dynamics and rainfall in western Indonesia, particularly during the boreal winter season. The domain for CENS identification is within the coordinates 0° 5°S and 105°E 115°E (the black box in Fig. 1) [4, 5].

The study period was selected during CENS-ENSO Neutral, CENS-La Niña, and CENS-El Niño events from 1998 to 2023, specifically during November-December-January-February-March (NDJFM). The selection of the NDJFM months is based on climatological studies which found that CENS can enhance daily rainfall in the Java Sea and the western part of Java [20]. Additionally, we used data periods from 1998 to 2023 due to the availability of CMORPH data, which allows for a comprehensive analysis of the atmospheric dynamics related to CENS and ENSO. Regarding the selection of specific ENSO events, i.e. El Niño, La Niña, and Neutral conditions were chosen because they have very different impacts on global atmospheric dynamics, included maritime continent. El Niño and La Niña events are known to significantly alter sea surface temperature patterns and atmospheric circulation, which in turn affects rainfall and humidity patterns in Indonesia [21, 22]. The number of occurrences of ENSO phases and CENS is shown in Fig. 2. According to the figure, the highest number of occurrences took place during the interaction of CENS with La Niña, with 182 events, followed by CENS with ENSO Neutral and CENS with El Niño,

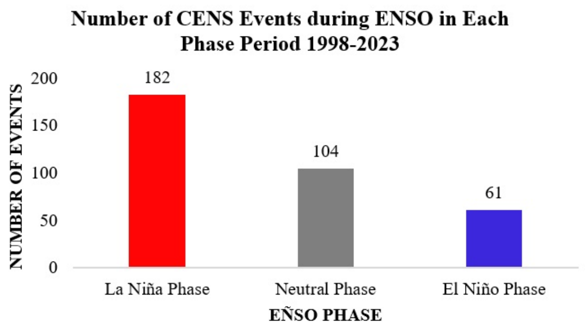

FIG. 2: Diagram of the number of CENS occurrences during ENSO.

with 104 and 61 events, respectively.

B. Data

The data used in this study include:

- ERA-5 reanalysis pressure level data with a spatial resolution of 0.25° x 0.25° and a temporal resolution of one hour, i.e. zonal wind (u), meridional wind (v), and specific humidity (q) at the 1000 mb - 825 mb layers to determine moisture transport [5], as well as meridional wind at the 925 mb layer to determine the CENS index. This data can be accessed through https://cds.climate.copernicus.eu/cdsapp!/dataset/reanalysis-era5-pressure-levels?tab=overview.
- ERA-5 reanalysis single level data with a spatial resolution of 0.25° x 0.25° and a temporal resolution of one hour, with parameters such as mean top net long-wave radiation flux (MTNLWRF) and sea surface temperature (SST). OLR data in this studies is negative value of MTNLWRF data. This data can be accessed through https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview.
- CMORPH High-Resolution Global data for precipitation estimation, with a spatial resolution of 0.25° x 0.25° and a daily temporal resolution. This data can be accessed through https://www.ncei.noaa.gov/data/cmorph-high-resolution-global-precipitation-estimates/archive/daily/0.25deg/.

C. Data Processing

In general, the collected data underwent an initial filtering process based on the timing of events, followed by the creation of anomalies for several meteorological parameters and the development of the CENS index using Climate Data Operators (CDO). The processed data were then analyzed using the Grid Analysis and Display System (GrADS) software to generate spatial maps, which were subsequently examined through descriptive quantitative analysis. QGIS software was utilized to produce maps of the research locations. Notepad++ was employed for creating and editing scripts used in GrADS and CDO software. Additionally, spreadsheet software was used for data processing in the identification of CENS-ENSO phenomena.

The data processing in this study consists of several steps, including the identification of CENS, identification of ENSO, spatial compositing of OLR anomalies, compositing of rainfall anomalies, compositing of SST anomalies, analysis of low-level moisture transport, and divergence analysis of low-level moisture transport. The identification of CENS is based on the study by [4], which states that CENS is considered to occur when the meridional wind speed (v) is less than -5 m/s in the area indicated by the black box in Fig. 1. The identification of the ENSO phenomenon is conducted using the Oceanic Niño Index (ONI), which represents the three-month running mean of sea surface temperature anomalies in the Niño 3.4 region (5°N - 5°S, 170°W - 20°W). An event is categorized as El Niño if the ONI value is +0.5°C and persists for five consecutive three-month periods. Conversely, a La Niña event occurs when the ONI is -0.5°C for five consecutive three-month periods. Neutral conditions, or ENSO-Neutral, are defined when ONI values range between -0.499°C and +0.499°C or do not meet the five-period consistency criteria for El Niño or La Niña. Further information regarding historical ONI data can be accessed at https://ggweather.com/enso/oni.htm.

In this study, anomalies of OLR, precipitation, and SST are processed using composite analysis based on the identified CENS and ENSO events over a 26-year period (19982023) during the boreal winter season (NDJFM). Each of these parameters is averaged using the arithmetic mean formula. The arithmetic mean is defined as the sum of all observed values divided by the total number of observations [23]. This formula is represented in Eq.(1) for the OLR anomaly composite, Eq.(2) for the precipitation anomaly composite, and Eq.(3) for the SST anomaly composite.

$$\bar{o} = \frac{\Sigma o_i}{n} \quad (1)$$

$$\bar{c} = \frac{\Sigma c_i}{n} \quad (2)$$

$$\bar{s} = \frac{\Sigma s_i}{n} \quad (3)$$

where $\bar{o}$ represents the composite OLR anomaly (W/m), o_i is the OLR value for each CENS-ENSO event (W/m), $\bar{c}$ denotes the composite precipitation anomaly (mm/day), c_i is the precipitation value for each CENS-ENSO event (mm/day), $\bar{s}$ represents the composite SST anomaly (°C), s_i is the SST value for each CENS-ENSO event (°C), and n is the total number of CENS-ENSO events.

The analysis of Low-Level Moisture Transport (LLMT) in this study aims to assess the influence of CENS and ENSO on the enhancement of convective activity and precipitation in the study area through moisture transport mechanisms. The LLMT analysis method follows [24], utilizing Equation 4 and processed using the GrADS with the vertical integral (vint)

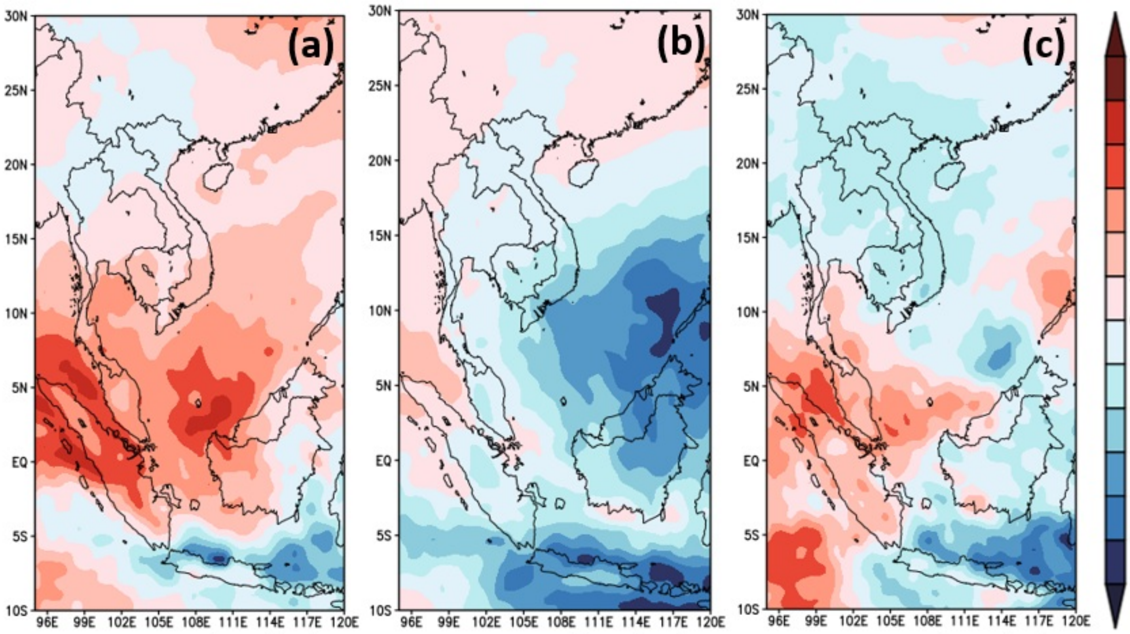

FIG. 3: Visualization of OLR anomalies (Watt/m) during the CENS phenomenon in the (a) Neutral, (b) La Niña, and (c) El Niño phases.

command. This command is used to calculate the vertical integration of a variable across various pressure levels in three-dimensional data.

$$Q = \frac{1}{g}\int_{pt}^{ps} q\vec{V}dp \tag{4}$$

where Q represents the moisture transport (kg/m/s), g is the gravitational acceleration of the Earth (9.81 m/s^2), ps is the surface pressure (1000 hPa), pt is the pressure at the upper level (825 hPa), q denotes the specific humidity (g/kg), $\vec{V}$ is the wind vector consisting of the zonal (u) and meridional (v) components in m/s, and dp represents the pressure difference (hPa).

The divergence was calculated by the finite difference method, specifically the hdivg command in GrADS. This study computed the divergence of LLMT using Eq.(5), based on [25].

$$\nabla_H \bullet q\vec{V} = \frac{\delta qu}{\delta x} + \frac{\delta qv}{\delta y} \tag{5}$$

where $\nabla_H \bullet q\vec{V}$ is the horizontal divergence of llmt (kg/m/s), qu represents the zonal moisture transport component (m/s), and qv represents the meridional moisture transport component (m/s).

III. RESULTS AND DISCUSSION

A. Cloudiness Anomaly when ENSO and CENS Occured

The radiation in Earth's atmosphere that can influence the weather conditions of a region is longwave radiation or OLR. During CENS and ENSO events, atmospheric conditions can be observed through the convection patterns in the region. The OLR value at the top of Earth's atmosphere is a function of two factors: the amount of cloud cover and the cloud surface temperature, both of which are related to convection [23]. Fig. 3 shows that during periods of active CENS under neutral ENSO conditions in Boreal winter, negative OLR anomalies were observed over several regions of Indonesia, particularly along the northern coast of Java, Bali, and the surrounding areas. This indicates an enhancement of convective activity in these regions compared to climatological conditions, thereby increasing the potential for extreme weather events. In contrast, positive OLR anomalies are evident over Sumatra and most of Kalimantan, suggesting a reduction in convective cloud cover relative to the climatological mean, leading to clearer skies in these areas. These findings are consistent with previous studies investigating the impacts of CENS on atmospheric dynamics in the western Maritime Continent [5], which reported an increase in convective cloud cover over Java, particularly along the western part of its northern coast, and a corresponding decrease over Sumatra and parts of Kalimantan.

During active CENS under La Niña conditions (Fig. 3.(b).), most western Indonesia exhibits negative OLR anomalies, except northern Sumatra and Aceh. This indicates an increase in convective cloud cover across the region. The presence of La Niña changes the convective cloud distribution over Sumatra and Kalimantan, which, under active CENS independently, typically experience reduced convective cloud cover (Fig 3.(a).). Instead, La Niña enhances deep convective cloud development in these areas. La Nina increased moisture and the westward shift of the warm pool toward western Indonesia.

Conversely, during active CENS under El Niño conditions (Fig 3.(c).), positive OLR anomalies are observed over Sumatra and some of Kalimantan, indicating a reduction in convective cloud cover and generally clear weather in these regions. However, enhanced convective cloud cover persists along the northern coast of Java, Bali, and the surrounding areas. This suggests that the strengthening of the Asian monsoon, driven by active CENS, balances for the reduced moisture and the eastward displacement of the warm pool associated with El Niño.

B. Rainfall Anomalies

Changes in atmospheric circulation during El Niño and La Niña cause rainfall anomalies in various locations. From a synoptic scale perspective, the flow of air masses from the Northern Hemisphere to the Southern Hemisphere supports the growth of convective clouds that can lead to rainfall [24]. The relationship between OLR and convective activity is key to understanding these rainfall anomalies, as variations in OLR reflect the intensity of convection and cloud cover, which directly influence precipitation.

Fig. 4.(a). shows rainfall anomalies during CENS events in the ENSO Neutral, northern Java Island and Java Sea exhibit positive rainfall anomalies ranging from 4 mm/day to over 10 mm/day. These increases in rainfall are consistent with the intensified convective activity and cloud development identified by the negative OLR anomalies during the Neutral phase, suggesting localized atmospheric instability and enhanced moisture transport. Conversely, negative OLR anomalies are observed in the northern parts of Sumatra and western Borneo, ranging from -8 mm/day to -1 mm/day. This indicates reduced rainfall in these areas, corresponding to weaker convection and lower moisture convergence, as reflected in the OLR analysis (Fig. 3.(a).). These findings are consistent with previous studies investigating the impacts of CENS on rainfall anomalies in the western Maritime Continent [5], which reported an increase rainfall over northern Java Island and Java sea, and a corresponding decrease over Sumatra and parts of Kalimantan.

During CENS events in the La Niña phase, rainfall anomalies show a similar spatial distribution but with slightly reduced intensity. Positive rainfall anomalies in the Java Sea, Java Island, and southern Borneo range from 4 mm/day to more than 10 mm/day. This aligns with the negative OLR anomalies observed during La Niña, indicating deep convective cloud formation (Fig. 3.(b).). However, the magnitude of these anomalies suggests that La Niña's influence may temper the usual convection-enhancing effects of CENS, resulting in less intense but still notable rainfall increases. In contrast, negative rainfall anomalies in northern Sumatra and western Borneo range from -6 mm/day to -1 mm/day, reflecting suppressed convection and stable atmospheric conditions.

In the El Niño phase, CENS events produce rainfall anomalies that mirror the ENSO Neutral phase in spatial distribution but differ in intensity. Negative rainfall anomalies in northern Sumatra and western Borneo range from -8 mm/day to -1 mm/day, indicating significant reductions in rainfall due to suppressed convection in these regions. This is somewhat unexpected, given that El Niño typically suppresses convection. However, the negative OLR anomalies during CENS suggest localized bursts of convective activity in other areas. The Java Sea, Java Island, and southern Borneo show positive anomalies ranging from 2 mm/day to over 10 mm/day, though these increases are generally more intense than in the Neutral phase. This suggests that while El Niño may enhance convection during CENS events in certain regions, the overall atmospheric stability limits widespread rainfall increases.

The spatial variability of rainfall anomalies across different ENSO phases highlights the complex interaction between CENS-driven atmospheric dynamics and ENSO-modulated sea surface temperatures. These anomalies are directly tied to the convection patterns and the amount of water vapor present in the atmosphere, as evidenced by OLR variations during CENS events. Understanding these interactions is crucial for improving precipitation forecasts and assessing the risk of hydrometeorological hazards in western Indonesia.

C. Sea Surface Temperature

Sea Surface Temperature (SST) in the waters of Indonesia serves as an index for the amount of water vapor involved in cloud formation in the atmosphere [25]. SST variations directly influence the atmospheric moisture content, which in turn affects convection patterns and rainfall anomalies, as reflected by changes in Outgoing Longwave Radiation (OLR). When the sea surface temperature is cooler, the amount of water vapor in the atmosphere decreases, leading to suppressed convection and reduced cloud development. Conversely, warmer sea surface temperatures increase atmospheric moisture, enhancing convective activity and rainfall potential.

Fig. 5 illustrates SST anomalies during CENS events across different ENSO phases. During CENS in the ENSO Neutral phase, SST anomalies are slightly negative, ranging from -0.4°C to -0.2°C, indicating a moderate reduction in the water vapor available for cloud formation due to cooler sea surface temperatures. This aligns with the negative OLR anomalies and the observed increase in rainfall in southern Sumatra, the Java Sea, and Java Island, suggesting that despite the slight cooling of SST, atmospheric convection remains active, possibly driven by enhanced moisture convergence from CENS-induced low-pressure systems.

In the La Niña phase, SST anomalies remain similarly negative, ranging from -0.4°C to -0.2°C, which typically indicates a reduction in available water vapor. However, the pos-

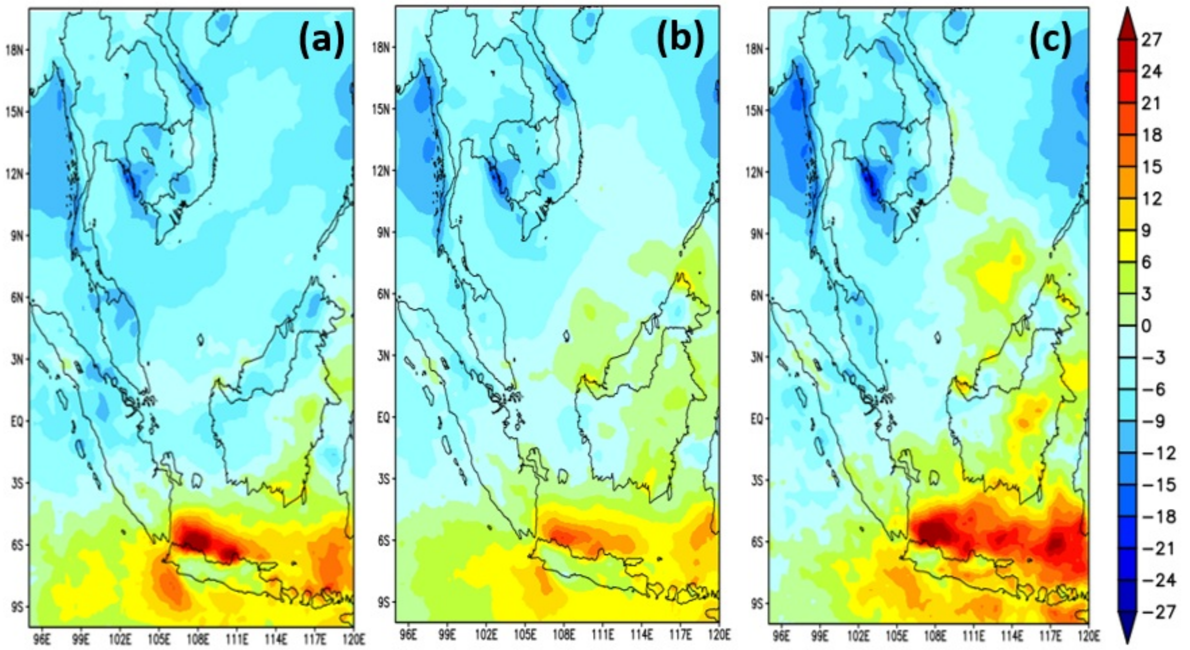

FIG. 4: Visualization of rainfall anomaly (mm/day) during the CENS phenomenon at the phases of (a) Neutral, (b) La Niña, and (c) El Niño.

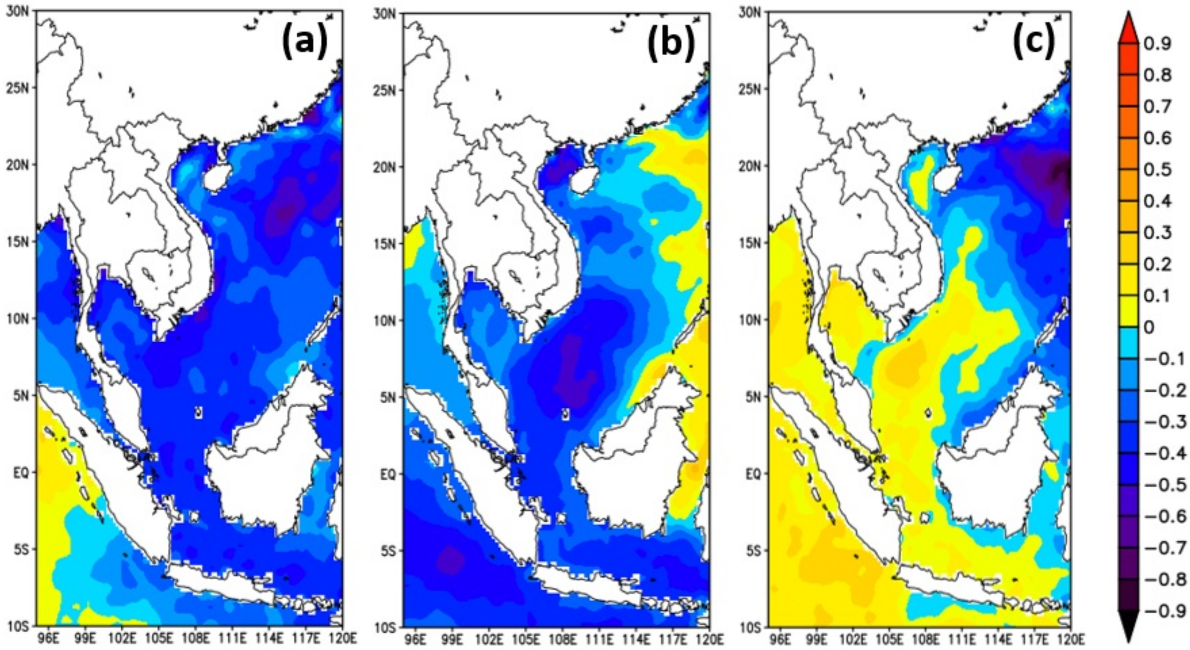

FIG. 5: Visualization of SST anomalies (°C) during the CENS phenomenon in the (a) Neutral, (b) La Niña, and (c) El Niño phases.

itive rainfall anomalies in southern Sumatra and Java during this phase suggest that other atmospheric factors, such as increased cross-equatorial moisture transport from CENS, may compensate for the cooler SST, sustaining localized convective activity. This is further supported by positive OLR anomalies, which point to suppressed convection in northern regions but allow for isolated convective events in southern areas influenced by moisture convergence.

During CENS in the El Niño phase, SST anomalies are distinctly positive, ranging from 2°C to 4°C, reflecting signif-

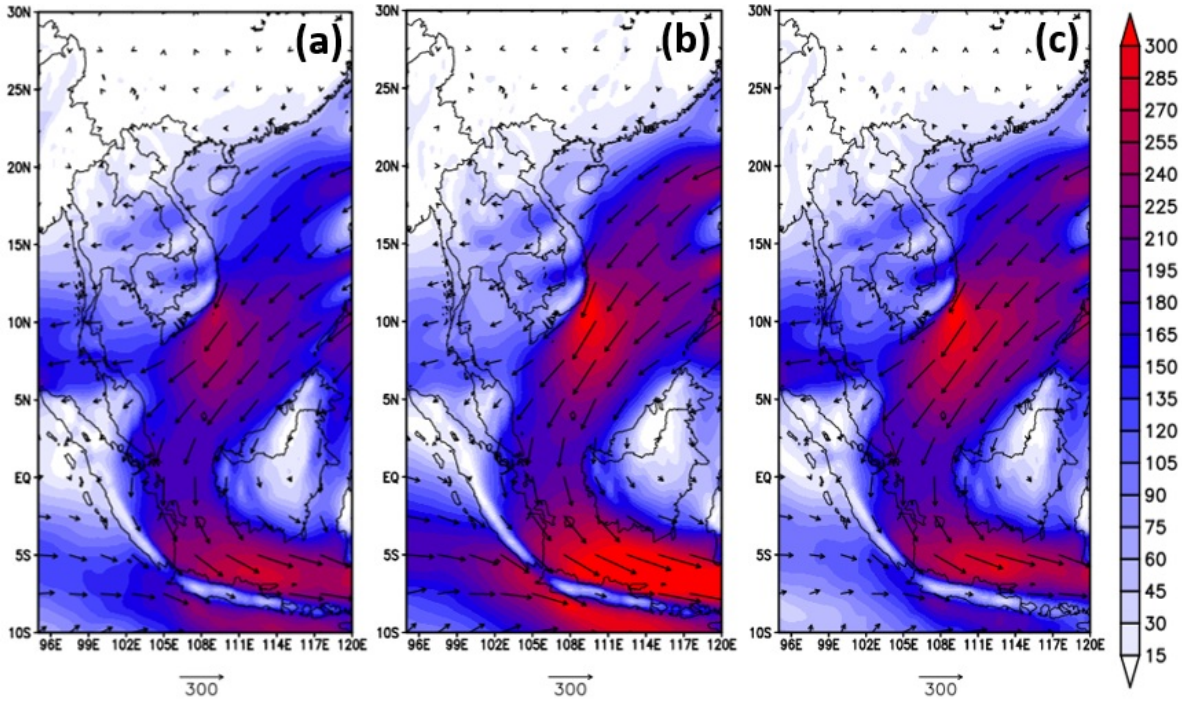

FIG. 6: Visualization of moisture transport (kg/m/s) during the CENS phenomenon in the (a) Neutral, (b) La Niña, and (c) El Niño phases.

icantly warmer sea surface temperatures and increased water vapor availability. This warming correlates with negative OLR anomalies, indicating intensified convective activity and greater cloud formation. However, the rainfall anomalies during this phase are mixed: while southern regions still experience increased rainfall, the intensity is generally lower compared to the Neutral phase. This suggests that while warmer SSTs enhance atmospheric moisture, the typical atmospheric stability associated with El Niño may limit widespread convective development, highlighting the complex interplay between oceanic and atmospheric dynamics during CENS events.

Overall, the interaction between SST anomalies, OLR patterns, and rainfall distribution across ENSO phases demonstrates the intricate coupling between oceanic conditions and atmospheric convection. These interactions result in varying convective responses, where factors like sea surface temperature and moisture transport influence the intensity and distribution of rainfall across western Indonesia. Understanding these relationships is essential for improving the predictability of precipitation patterns and assessing the risk of extreme weather events in the region.

D. Moisture Transport

Moisture transport analysis is conducted to understand the impact of CENS on atmospheric dynamics in the study area. The moisture transport analysis in this study is based on the method of Zhou and Yu [26]. The analysis of low-level moisture transport in the 1000 to 825 mb layer clearly illustrates the distribution of air mass entering the Indonesian region. Low-level moisture transport is a critical factor influencing convection, as it supplies the water vapor necessary for cloud formation and precipitation, which is reflected the OLR and rainfall anomalies.

Fig. 6 shows that during all ENSO phases, there is consistent cross-equatorial airflow from the Northern Hemisphere into Indonesia. However, the intensity of moisture transport differs based on the specific ENSO phase, which directly affects convection and rainfall patterns. Fig. 6b, representing CENS during La Niña, shows the most intense moisture transport, indicated by deeper red shading over southern Sumatra, the Java Sea, and northern Java. This is followed by Fig. 6.(c) (CENS-El Niño) and Fig. 6.(a) (CENS-Neutral), indicating weaker moisture transport. During CENS in the ENSO Neutral phase, moisture transport ranges from 45 kg/m/s to 255 kg/m/s. These findings are consistent with previous studies investigating low-level moisture transport during CENS in the western Maritime Continent [5]. This moderate influx of moisture corresponds with slightly negative SST anomalies (-0.4°C to -0.2°C), yet negative OLR anomalies and positive rainfall anomalies in Northern Java Island, and the Java Sea suggest that CENS-induced moisture convergence compensates for cooler SST, sustaining active convection. This highlights the role of atmospheric dynamics in maintaining convective processes despite limited oceanic moisture contributions.

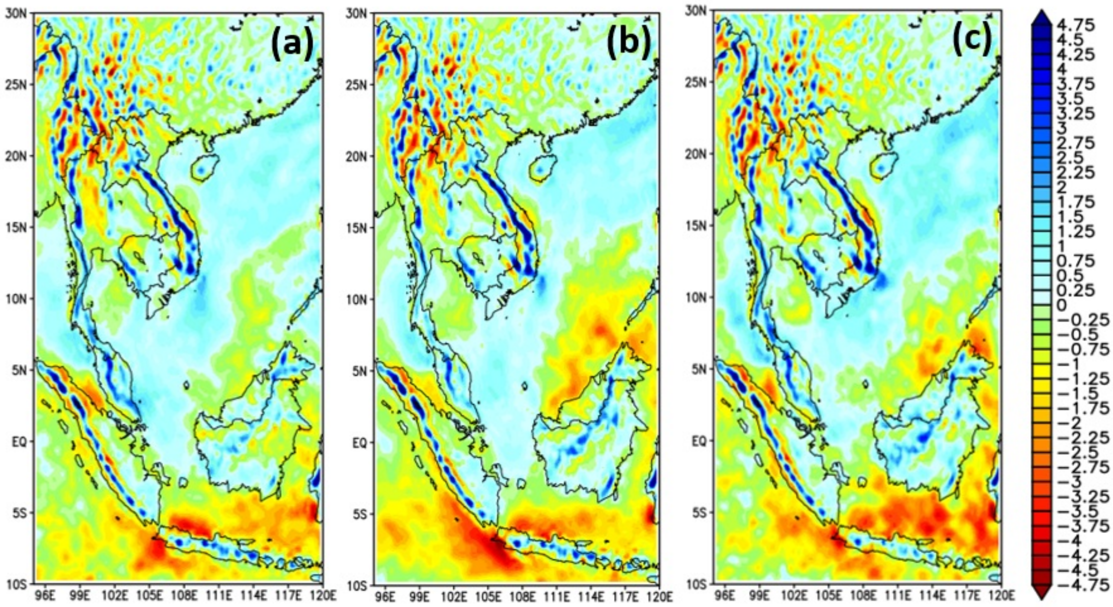

FIG. 7: Visualization of divergence (10/s) during the CENS phenomenon in the (a) Neutral, (b) La Niña, and (c) El Niño phases.

In the La Niña phase, moisture transport is notably stronger, ranging from 45 kg/m/s to over 300 kg/m/s, particularly from the South China Sea to the Java Sea. Despite slightly negative SST anomalies during La Niña, the substantial cross-equatorial moisture transport enhances convection, as evidenced by localized negative OLR anomalies and increased rainfall in southern regions. This indicates that CENS-driven moisture influx can override the suppressive effects of cooler SST, leading to intensified rainfall, especially in southern Sumatra and Java.

During CENS in the El Niño phase, significant moisture transport is observed, ranging from 45 kg/m/s to 270 kg/m/s. This is accompanied by positive SST anomalies (2°C to 4°C), which increase atmospheric water vapor availability. However, while negative OLR anomalies suggest active convection, the corresponding rainfall anomalies are less pronounced compared to the Neutral and La Niña phases. This suggests that El Niño-induced atmospheric stability may limit the effectiveness of moisture transport in generating widespread precipitation, even when moisture and convection are present.

Overall, the interplay between moisture transport, SST anomalies, and OLR patterns across ENSO phases highlights the complexity of atmospheric responses to CENS events. These interactions vary significantly across different regions, leading to spatially diverse rainfall patterns that cannot be attributed to a single atmospheric or oceanic factor. Moisture transport enhances convection and rainfall, but its effectiveness is modulated by sea surface temperatures and broader atmospheric circulation patterns, emphasizing the need for integrated analyses to improve precipitation forecasting in western Indonesia.

E. Divergence

Divergence is the horizontal reduction of low-level moisture transport from a region on the Earth's surface, which can lead to a decrease in air pressure [31, 32]. This parameter is crucial in understanding atmospheric dynamics, as divergence and its counterpart, convergence, directly affect cloud formation and rainfall distribution. Based on Fig. 7, as a result of the CENS phenomenon during the ENSO Neutral, La Niña, and El Niño phases in the Java Sea waters, negative divergence values ranging from -3 $\times$ 10^{-4}/s to 0.25 $\times$ 10^{-4}/s are observed. These negative values indicate convergence, where air masses accumulate due to cross-equatorial flow from the Northern Hemisphere, enhancing convective activity and contributing to the increased rainfall observed in the Java Sea, and Northern Java Island. These result are consistent with previous studies investigating divergence of low-level moisture transport during CENS in the western Maritime Continent [5], which showed an increase rainfall over northern Java Island and Java sea.

In contrast, positive divergence values are evident along the western part of Sumatra, ranging from 2.75 $\times$ 10^{-4}/s to over 4.75 $\times$ 10^{-4}/s, indicating divergence where air moves eastward toward Sumatra. This divergence corresponds with reduced convective activity and lower rainfall in these regions, as reflected in the positive OLR anomalies and negative rainfall anomalies observed during CENS events. The spatial distribution of divergence across different ENSO phases highlights how variations in atmospheric circulation, driven by SST anomalies and moisture transport, modulate local weather patterns.

Overall, divergence patterns in the region illustrate the complex interplay between atmospheric dynamics and oceanic conditions, where convergence zones enhance rainfall and divergence zones suppress it. These patterns are closely linked to variations in OLR, SST, and low-level moisture transport, which collectively influence convective activity and precipitation distribution. Understanding these interactions provides a more comprehensive framework for assessing precipitation variability and improving weather prediction in western Indonesia.

IV. CONCLUSION

The analysis of atmospheric dynamics during CENS events across different ENSO phases reveals that under neutral ENSO conditions, the atmospheric response to CENS is consistent with previous studies. As a Northerly Cold Surge (NCS), CENS leads to cooler SST over the SCS. However, the strengthening of the Asian monsoon induced by CENS enhances moisture transport toward Java and its surrounding regions, particularly along the western part of the northern coast of Java. Additionally, this region experiences moisture transport convergence, further supporting the development of deep convective clouds and increasing precipitation. In contrast, despite receiving significant moisture transport from CENS, Sumatra and parts of Kalimantan exhibit moisture transport divergence. As a result, cloud cover in these regions is reduced compared to climatological conditions, leading to clearer skies and decreased precipitation.

During CENS events under La Niña conditions, SST anomalies over the SCS remain negative, indicating cooler-than-climatological conditions. However, during this period, the Maritime Continent receives more moisture transport than neutral ENSO conditions. Additionally, regions such as Kalimantan, which previously experienced moisture divergence under neutral ENSO, instead undergo moisture convergence during La Niña. This shift enhances convective cloud development and increases precipitation over the region. As a result, the spatial extent of areas experiencing enhanced convective cloud cover and precipitation is more than when CENS occurs independently.

During CENS events under El Niño conditions, the cooling effect on SST in SCS induced by CENS is no longer evident, as SST anomalies shift to positive values. Despite this, moisture transport remains substantial, though lower than during La Niña. Additionally, regions experiencing moisture convergence expand, particularly over the Java Sea. The presence of warmer SST enhances evaporation in this region, and although El Niño generally suppresses convection, the role of CENS in increasing moisture transport and enhancing convergence over the Java Sea encourages convective cloud formation and leads to increased precipitation in the area.

These findings underscore the critical role of CENS-ENSO interactions in modulating regional weather patterns, offering valuable insights for atmospheric science. Understanding these dynamics is essential for improving weather forecasting models, particularly in predicting extreme weather events like floods and prolonged rainfall in western Indonesia. The research also holds implications for disaster preparedness and mitigation policies, enabling more accurate risk assessments and early warning systems for vulnerable regions affected by hydrometeorological hazards. Furthermore, this study contributes to broader climate research by highlighting how cross-equatorial atmospheric processes interact with global phenomena like ENSO to influence local weather variability.

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