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Impact of Indian Ocean Vortices on Convective Activities in Western Indonesian Maritime Continent

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Abstract. *The Indian Ocean plays a critical role in modulating global and regional atmospheric circulation, directly influencing weather systems and energy-related processes over the western Indonesian Maritime Continent (IMC). One of the key synoptic-scale disturbances in this region is the Indian Ocean cyclonic vortex, which can significantly impact convective activity and, consequently, the availability and variability of renewable energy sources such as solar and wind energy. This study investigates the characteristics and atmospheric effects of 30 cyclonic vortex events over the Indian Ocean during the eastern monsoon period (May–September) from 2018 to 2022. Using high-resolution ERA5 reanalysis data (hourly, 0.25° × 0.25°) including sea surface temperature (SST), potential vorticity, specific humidity, precipitation, and 850 hPa winds, the vortices were classified into eastern (90°–105°E) and western (75°–90°E) groups, consisting of 17 and 13 cases, respectively. Results show that eastern vortices are generally associated with warmer SSTs (≥30.5°C) near 7°S, 99°E and exhibit stronger cyclonic circulation centered at approximately 875 hPa. These eastern vortices induce significant convective enhancement over western Sumatra through the formation of organized squall lines extending from Subulussalam to Tebing Tinggi (95°–102°E), which may influence cloud cover, rainfall intensity, and local solar irradiance. In contrast, western vortices, despite forming deep convective clouds over the ocean (90°–95°E), have limited impact on land-based convection. Both types of vortices contribute to the formation of broad convective bands stretching from western Sumatra to East Java, Bali, Lombok, and Nusa Tenggara (100°–115°E), which can affect short-term variability in solar and wind energy harvesting. These findings highlight the importance of understanding atmospheric disturbances over the Indian Ocean for developing reliable and resilient renewable energy strategies in western Indonesia.*

Keywords: Vortex, Sea surface temperature anomaly, Western Indonesian Maritime Continent (IMC), Convective activity.

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Introduction

Climate change poses a significant threat to nations worldwide, prompting the urgent need to transition energy systems away from fossil fuels and toward renewable sources of electricity generation [1]. The potential for renewable electricity in Indonesia is substantial, thanks to its tropical equatorial climate, which ensures consistent solar radiation throughout the year and stable seasonal monsoon winds [2]. However, Indonesia has not yet fully leveraged its solar and wind energy potential, as reflected by the limited deployment of solar and wind power plants. Wind energy utilization is restricted to a single operational site in South Sulawesi [3].

Indonesia's vast wind energy potential stems from its geographical position as part of the Indonesian Maritime Continent (IMC), between Asia and Australia, bordered by the Pacific and Indian Oceans. This location results in two dominant monsoon systems—Asian and Australian. Research has identified key monsoon-influenced regions in Indonesia: Index I areas in the north (2°–8°S, 95°–118°W) and Index II areas in the south (2°–10°N, 105°–150°E) of the equator [4]. These findings highlight the importance of integrating wind energy potential into climatological studies on monsoon winds. Large-scale weather disturbances, such as the Vortex, can disrupt monsoon wind patterns, particularly in western Indonesia.

The Indian Ocean is one of the most critical water areas and vital to the global climate system. Vortices are an essential type of weather system that can be used to track and analyze weather patterns, especially for finding dangerous weather and strong convection [4]. Mesocyclones often bring tornadoes, hail, and damaging winds; cold vortices over northeast China bring rainstorms; and tropical cyclones, which bring devastating typhoons, are among the most significant atmospheric vortices [5]. Most algorithms used to detect small-scale vortices are based on radar data in meteorology [6], [7]. Large-scale vortices are based on detecting low-pressure centers in fused or isometric local topographic height data [8], [9].

Based on previous studies, the formation of vortex centers is associated with topographic blocking and the effects of vorticity anomalies in the upper troposphere moving to the surface [10]. Differences or deviations in vorticity from normal or area-average values are known as vorticity anomalies. Locations of greater vorticity may also have wind shear and violent wind fields in addition to vorticity [11]. In dynamic meteorology, the paramount importance of vorticity is often associated with the vertical components of absolute vorticity and relativistic vorticity, from which its ability to change the size of the vertical column of air up or down is represented by positive or negative values for its direction of motion [12]. Analysis of the formation mechanism and vortex characteristics can be obtained using potential vorticity analysis [10], where this analysis is quite widely done to study atmospheric phenomena such as diagnosis of cyclone development and movement. An extended method [13] has been proposed using spatial smoothing techniques to control the scale of the targeted vortex, reduce the sensitivity of the analyzed vortex features, and for model mesh resolution. Other objective methods have been used to identify vortices and detect their centers in 2D flows. Examples are traditional methods based on the concept of a single center point for continuous linear flow fields [14], approaches based on simplified topology [15], and point set conceptual methods for the discrete analysis of flow fields [16].

The vortex plays a role in regulating seasonal patterns and decreasing rainfall and drought when the vortex is inactive. The influence of the Indian Ocean vortex is also related to the El Niño and La Niña phenomena [17]. El Niño and La Niña are changes in sea surface temperatures in the Central and East Pacific regions that can affect global atmospheric circulation [18]. These

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conditions are associated with changes in wind patterns and temperature distribution in the Indian Ocean, which can affect convective activity over western Indonesia.

Materials and Methods

In the scale of variation of the analysis domain focused on each point, the vortex can be determined based on the trend of wind direction and the degree of horizontal deformation. The location of this study is around the Indonesian Sea area to the Indian Ocean, including parts of the South China Sea, parts of the Philippine Sea, Indonesia, Singapore, Malaysia, Brunei, and Timor Leste with boundaries of 105°–109°E and 5.5°–8°N (**Figure 1**).

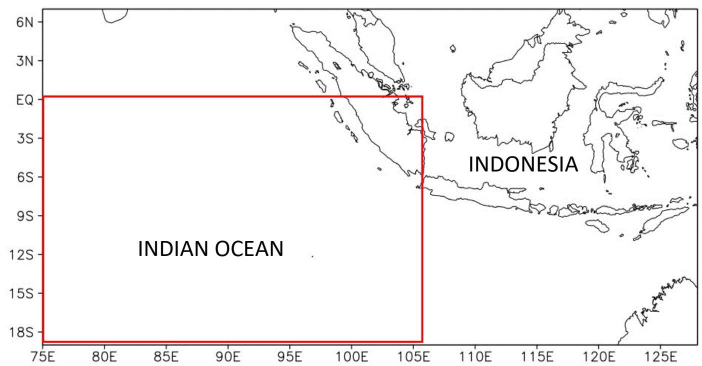

Figure 1. Research the location of vortex characterization in the eastern Indian Ocean south of the equator. The red box represents the identified vortex area (75˚–90˚E and 90˚–105˚E).

The time used in this study is data for each east monsoon season (May–September) for 5 years starting from 2018–2022. In the development of vortex characterization, this time consists of 4 variables in the form of phenomenon data and ocean-atmosphere parameters. The data used are: (1) hourly rainfall data obtained from GsMAP; (2) zonal and meridional wind data, temperature, specific humidity, potential vorticity, and CLWC (Cloud Liquid Water Content) obtained by the European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis 5th Generation (ERA5) which can be downloaded via Copernicus. EU with a spatial resolution of 0.25˚ × 0.25˚ and hourly temporal at 13 pressure levels (925 hPa to 500 hPa); (3) Sea surface temperature data were obtained from ERA5 with a spatial resolution of 0.25˚ × 0.25˚ and hourly temporal; (4) The vortex phenomenon in the eastern Indian Ocean (75˚–90˚E; 90˚–105˚E) was observed through SADEWA with hourly temporal resolution.

Table 1. Vortex characterization criteria

Group	Criteria	Case Identification	Total Cases
West Vortex	75˚– 90˚E	28 May 2018, 29 May 2018, 30 May 2018, 31 May 2018, 1 June 2018, 2 June 2018, 2 July 2021, 3 July 2021, 27 August 2022, 28 August 2022, 29 August 2022, 30 August 2022, 31	17

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Group	Criteria	Case Identification	Total Cases
		August 2022, 1 September 2022, 2 September 2022, 8 September 2022, 9 September 2022	
East Vortex	90° – 105°E	8 June 2018, 7 May 2020, 8 May 2020, 20 May 2020, 21 May 2020, 22 May 2020, 2 June 2021, 26 May 2022, 27 May 2022, 13 June 2022, 14 June 2022, 28 July 2022, 29 July 2022	13
		Total	30

Source: Personal categorization results.

A vortex is identified when circulating winds at a pressure of 925 hPa in the study area exhibit clockwise circulation with wind speeds exceeding 2m/s within a 2.5° × 2.5° square grid of the vortex center [19].

Potential vorticity is an analysis conducted to identify the potential occurrence of vortices or eddies on an object. The results can be used to develop new designs that are more efficient and reduce the potential for damage and wear to the object. Potential vortices are calculated at the isentropic level [10]. The data used is pressure level data, so each component must be interpolated at the isentropic level to calculate potential vortices.
Equation (1) defines isentropic potential vorticity:

$$P_V = -g\zeta_a\left(\frac{\partial\theta}{\partial p}\right) \tag{1}$$

Equation (2) defines absolute vorticity as:

$$\zeta_a = \zeta + f \tag{2}$$

PV is isentropic coordinate potential vorticity, g is the acceleration due to gravity, ζ_a is absolute vorticity, θ is potential temperature, ζ is relative vorticity.

Where $\zeta = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$ and f is the coriolis parameter

u = wind speed component in horizontal direction (east – west)

v = wind speed component in vertical direction (north – south)

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$\frac{\partial v}{\partial x}$ = change in vertical wind speed component along horizontal direction

$\frac{\partial u}{\partial y}$ = change in horizontal wind speed component along vertical direction

The data analysis begins by interpolating meteorological data from standard pressure to isentropic levels. This is essential for accurately computing PV values. Once the data is in isentropic form, potential vorticity is calculated using Equation (1) by combining the vorticity obtained from wind speed derivatives with the stratification indicated by the vertical gradient of potential temperature. Anomalies in PV are then determined by comparing current values with long-term climatological means, helping to identify regions with significant vortex activity. To better understand typical patterns, a composite analysis is conducted using Equation (3)

$$X_c = \frac{\sum X_i}{n} \tag{3}$$

Description:

X_c = composite average.

X_i = variable value at the i-th location or time.

n = number of locations or time periods.

This step allows the identification of common PV structures associated with specific weather events or regions. This analysis provides valuable insights into atmospheric vortices behavior and can inform meteorological forecasting and structural design considerations sensitive to such dynamics.

Results and Discussion

The analysis's results selected 30 vortex systems, which were divided into two: the evolution of the vortex system moving westward (western vortex) at the location of 90º–105ºE with 13 case studies and the evolution of the vortex system moving eastward (eastern vortex) at the location of 75º–90ºE with 17 case studies.

A. Characteristics of Eastern Vortices

In some cases, vortices can move eastward and can be affected by several factors, such as Sea Surface Temperature (SST) activity, atmospheric pressure, wind direction, and precipitation. Some analysis related to the evolution of an eastward-moving vortex system is shown in **Figure 2**.

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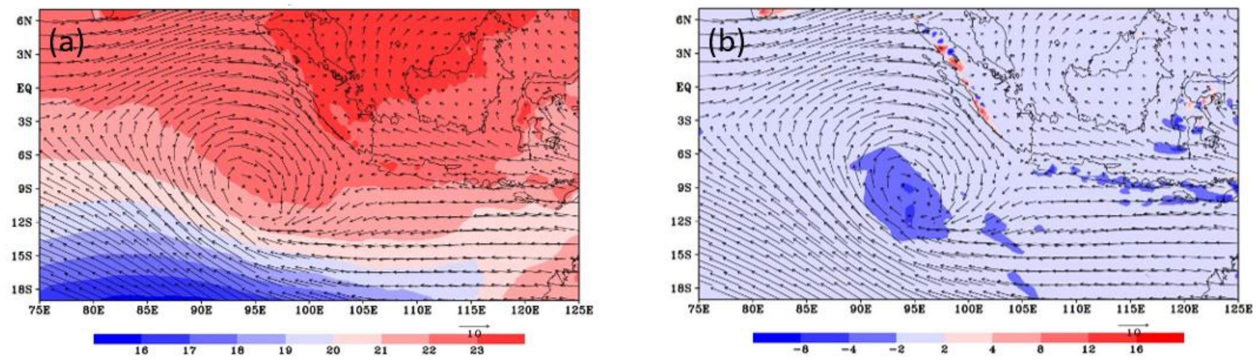

Figure 2. Composite spatial maps for a) wind anomalies at 925 mb (vector) and 2 m surface temperature (color grading) and b) potential vorticity ((1PVU) = 10–6 m2 s^{-1} K kg^{-1}) and wind at 925 mb (vector) during the eastern vortex (2018–2022).

On the composite spatial map of wind and temperature anomalies, the influence of the vortex at the location of 9˚S; 95˚E brings significant influence from tropical cyclones to affect the weather in the Indonesian region—air pressure differences due to high-pressure patterns in the Indian Ocean. On the spatial map of potential vorticity anomalies, it is known that vorticity increases at 925mb right at the center of vorticity marked with darker colors where it also causes impacts to southern Indonesia, especially in northern Sumatra, Sulawesi, Java, Bali, Lombok, and Nusa Tenggara. It is suspected that small cyclonic influences may occur, such as tornadoes, strong winds, and so on. **Figure 3** shows same as **Figure 2**, but for a) sea surface temperature (color grading (˚C) and wind at 850 mb (vector) and b) rainfall from the GSMaP satellite.

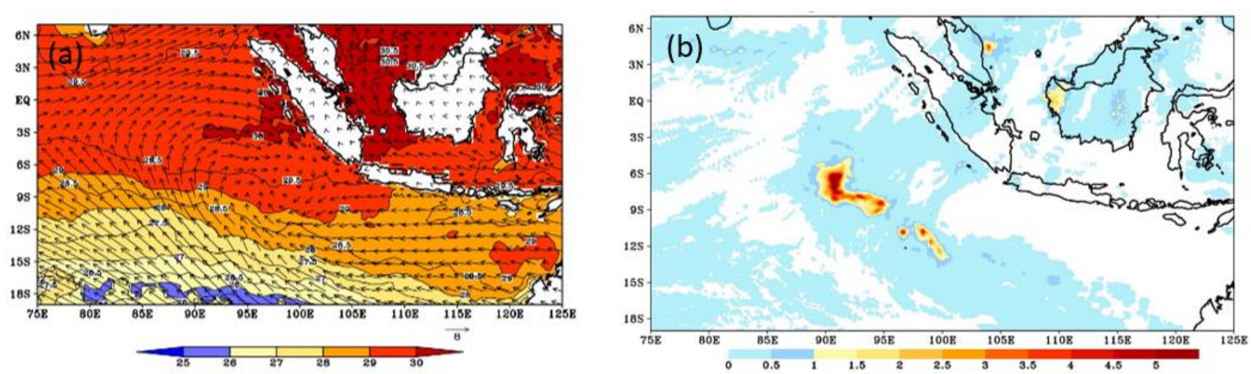

Figure 3. Same as Figure 2, but for a) sea surface temperature (color grading (˚C) and wind at 850 mb (vector) and b) rainfall from the GSMaP satellite.

On the spatial map of Sea Surface Temperature (SST), the center of the vortex is located at 6˚S; 99˚E, which is marked with dark colors, indicating that the dominant temperature is high or warming, especially in the South China Sea region, which has temperatures up to 30.5˚C. This significantly impacts weather changes in several areas of Indonesia, which is further strengthened by the spatial map of rainfall. The influence of the western vortex in the Indian Ocean Sea by forming squall lines significantly affects convective activity on land, especially in northern Sumatra, western Kalimantan, and western Java. **Figure 4** shows Same as Figure 3, but for

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longitude-altitude Hovmöller for a) zonal winds at 500–925 mb (contours) and potential vorticity ((1PVU) = 10–6 m2 s^{-1} K kg^{-1}) and b) Cloud Liquid Water Content (CLWC) at wind heights of 500–750 mb (vector).

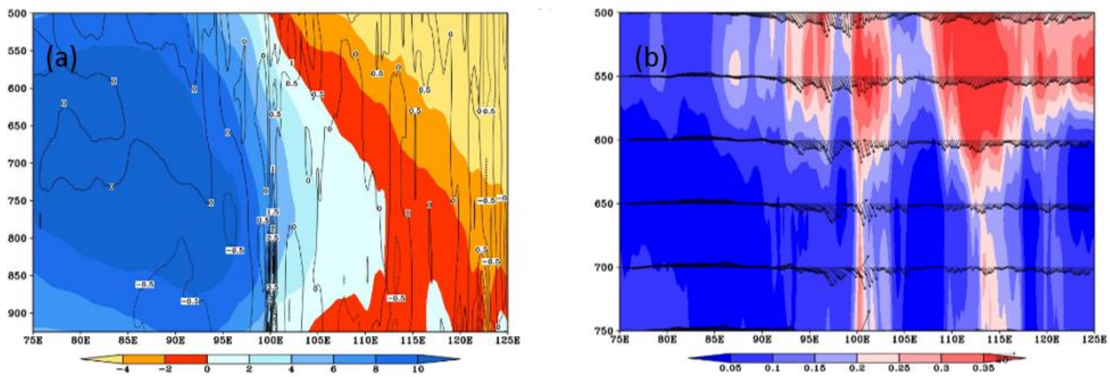

Figure 4. Same as Figure 3, but for longitude-altitude Hovmöller for a) zonal winds at 500–925 mb (contours) and potential vorticity ((1PVU) = 10–6 m2 s^{-1} K kg^{-1}) and b) Cloud Liquid Water Content (CLWC) at wind heights of 500–750 mb (vector).

On the Hovmöller map, the zonal winds and potential vorticity of the vortex center are in the red circle where the contours are very tight. Another thing that can be found on this Hovmöller map is that the westerly wind is stronger than 10m/s in the 875 hPa layer. This zonal wind controls the vortex. If you look at the color of the wind is divided into two parts: blue and orange, where the orange color is used to distinguish the direction of the wind. Winds with minus values are east winds, and winds with positive values are west winds. The influence of the eastern vortex on Indonesia is reinforced by CLWC's Hovmöller map, where deep convective clouds are found to form stretching from western Sumatra (100˚E) to East Java – Bali – Lombok – Nusa Tenggara (115˚E).

B. Characteristics of Western Vortices

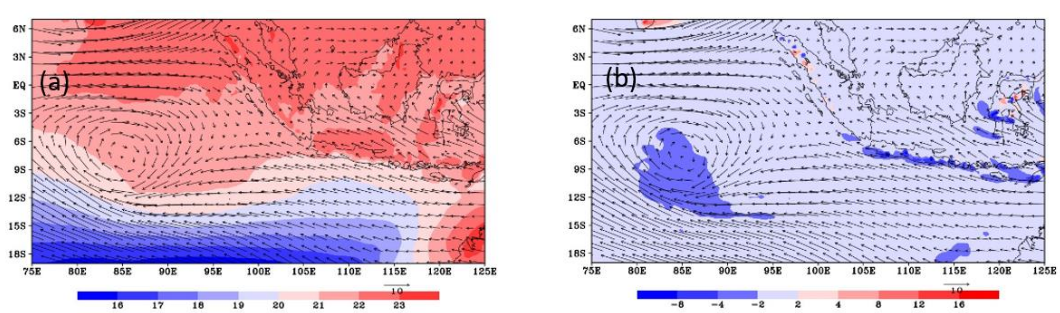

Figure 5. Same as Figure 2, but for the western vortex.

On the spatial map of wind and temperature anomalies, the influence of the vortex at the location 7˚S; 85˚E brings significant influence from tropical cyclones to affect the weather in the Indonesian region—air pressure differences due to high-pressure patterns in the Indian Ocean. On the spatial map of potential vorticity anomalies, it is known that vorticity increases at 925 mb right at the

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center of vorticity marked with darker colors where it also causes impacts to southern Indonesia, especially in northern Sumatra, Sulawesi, Java, Bali, Lombok, and Nusa Tenggara. It is suspected that small cyclonic influences may occur, such as tornadoes, strong winds, and so on. **Figure 5** shows same as **Figure 2**, but for the western vortex.

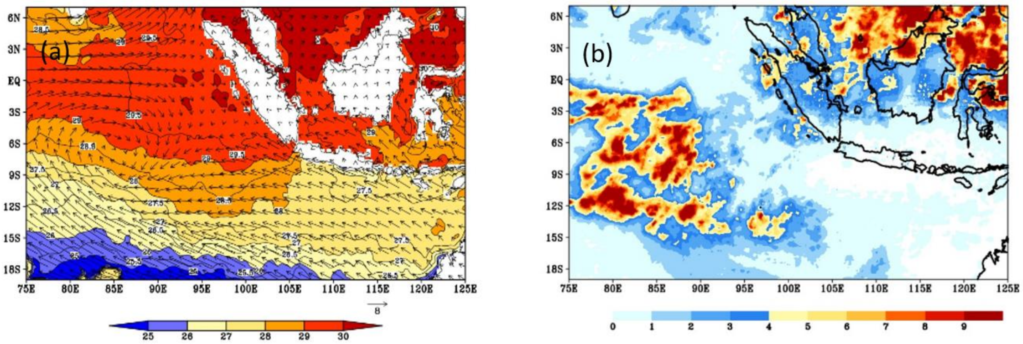

Figure 6. Same as Figure 3, but for the western vortex.

On the spatial map of Sea Surface Temperature (SST), the center of the vortex is at 7˚S; 85˚E, which is marked by darker colors, indicating that the dominant temperature is high or there is warming, especially in the South China Sea region, which has temperatures up to 29.5˚C. This significantly impacts weather changes in many areas of Indonesia, which is further strengthened by the spatial map of rainfall. The results of the study also found a significant influence of the western vortex on increasing convective activity on land, especially in west Sumatra, through the formation of a squall line that stretches from Subulussalam to Tebing Tinggi (95º – 102ºE). **Figure 6** shows same as **Figure 3**, but for the western vortex.

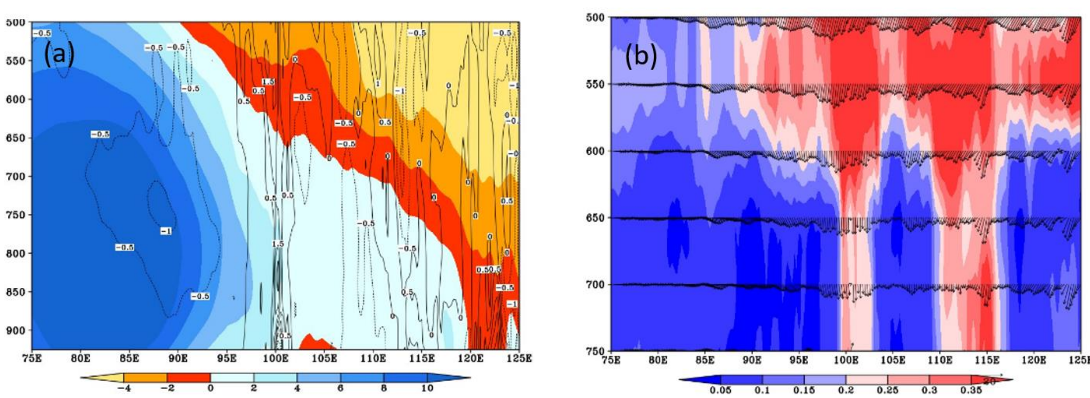

Figure 7. Same as Figure 4, but for the western vortex.

On the Hovmöller map, the zonal winds and potential vorticity of the vortex center are in the red circle where the contours are very tight. Another thing that can be found in this Hovmöller map is that the westerly wind is stronger than 10m/s in the 800 hPa layer. This zonal wind controls the vortex. The influence of the western vortex on Indonesia is reinforced by CLWC's Hovmöller map, where deep convective clouds are found to form stretching from western Sumatra (100˚E) to East Java – Bali – Lombok – Nusa Tenggara (115˚E). **Figure 7** shows Same as **Figure 4**, but for the western vortex.

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Conclusions

The results selected 30 vortex systems divided into two, viz: eastern (western) vortices with a location of 75º–90ºE (90º–105ºE) and 17 (13) case studies, respectively. This research ensures a thorough and balanced analysis of both types of vortices so that they are representative. The results also show a 1˚C difference in SPL warmth for the western (eastern) vortex at 7˚N; 85˚E (6˚S; 99˚E) with temperatures ≥29.5˚C (≥30.5˚C). In addition, there are differences in the center of the vortex, with the most substantial magnitude occurring in the 800 hPa isentropic layer (875 hPa). Convective processes often happen in the 800 hPa layer. In this layer, the intensity of vortices can be enhanced by convective activities such as cloud formation and thunderstorms. This layer is often where vertical air movement is most active, contributing to vortices' formation and strengthening. The results of the study also found a significant influence of the eastern vortex on increasing convective activity on land, especially in western Sumatra, through the formation of a squall line stretching from Subulussalam to Tebing Tinggi (95º–102ºE). Meanwhile, the influence of the vortex of the west in the Indian Ocean Sea (90º–95ºE) through the formation of squall lines does not significantly affect convective activity on land. Both vortices create a strong convective cloud (deep convective cloud) that stretches from western Sumatra (100ºE) to East Java – Bali – Lombok – Nusa Tenggara (115ºE). By combining these results, this study has shed light on the complex dynamics of the BV phenomenon and how it impacts rainfall and weather in the Maritime Continental Shelf region. These findings provide a basis for long-duration (14 days) extreme weather that could disrupt the sustainability of wind energy supply in western Borneo and the surrounding area, which could be a consideration for the planning and operationalization of wind power plants in the region.

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