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Behavior of A Long-lived Borneo Vortex During March 2023

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Abstract. *The Borneo Vortex (BV) is a mesoscale cyclonic circulation centered over the South China Sea (SCS) that typically persists for 1–3 days and significantly influences convective activity in surrounding regions, including Indonesia. However, the behavior and impacts of long-lived BV events remain poorly understood. This study investigates the atmospheric characteristics and convective effects of a strong and long-lived BV event that occurred from March 2–10, 2023. Using ERA5 reanalysis data with high temporal (hourly) and spatial (0.25° × 0.25°) resolution, we analyzed wind, relative vorticity, specific humidity, Outgoing Longwave Radiation (OLR), and precipitation. The event was classified into three phases: pre-BV (February 25–March 1), during-BV (March 2–10), and post-BV (March 11–15), using a composite analysis approach. Results show enhanced convective activity and widespread precipitation over western Kalimantan and western Java during the pre-BV phase, associated with low-level convergence and warm sea surface temperatures (~28 °C) in the central SCS. During the BV phase, convection shifted toward the ocean, with intensified precipitation over the SCS and suppressed rainfall over land, likely influenced by downdraft formation over the Java Sea. In the post-BV phase, a squall line developed over the Java Sea, leading to renewed convective activity and increased precipitation over Kalimantan and western Sumatra. These findings highlight the importance of long-lived BV events in modulating regional weather patterns and suggest implications for short-term weather forecasting and renewable energy planning in Indonesia.*

Keywords: Borneo Vortex, South China Sea, Indonesian Maritime Continent, convective activity

Introduction

Climate change poses a significant threat to nations worldwide, prompting a shift towards sustainable energy solutions [1], [2]. One promising approach to addressing climate change is transitioning from fossil fuels to renewable energy sources. In Indonesia, the rich abundance of natural resources presents a unique opportunity, as the country, positioned in the equatorial tropics, receives consistent solar radiation throughout the year and experiences stable seasonal monsoon winds [3]. Despite this potential, Indonesia has not yet fully harnessed renewable

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energy, particularly solar and wind power generation. Currently, only one notable wind energy site is located in South Sulawesi, highlighting the need for further development in these areas [4].

The potential for wind energy in Indonesia is substantial due to its designation as the Indonesian Maritime Continent (IMC) between Asia and Australia, flanked by the Pacific and Indian Oceans. The country experiences two distinct monsoon systems—those of Asia and Australia. Previous studies have identified a monsoon index specific to Indonesia, revealing regions significantly affected by these two monsoons: Index I areas in the north (2˚–8˚N, 95˚–118˚E) and Index II areas in the south (2˚–10˚S, 105˚–150˚E) of the equator. This indicates the importance of considering wind energy potential in Indonesia's climatological studies of monsoon winds. Furthermore, synoptic-scale weather disturbances can interfere with the monsoon wind circulation patterns in the northern region, particularly around Borneo, a phenomenon known as the Borneo Vortex (hereafter BV).

The BV is a cyclonic weather system often associated with extreme precipitation and flooding in Southeast Asia. Vortices generated by wind friction, amplified by the convergence of northeast monsoon winds with the topography of Borneo, form the BV [5]. The BV is responsible for most of the extreme precipitation during the Borneo northern monsoon (up to 60 to 70% of the total extreme precipitation above the 95th percentile of daily precipitation rate) and 15 to 25% of the extreme precipitation on the east coast of Peninsula Malaysia during the northeast monsoon [6]. While propagating toward the equator, these weather systems can cause heavy precipitation and flooding in some areas of Indonesia [7]. Circulation across the equatorial SCS is strongly influenced by the variations and life cycle of the Borneo vortex, often referred to as the BV. The BV has a radius of up to 1000 km, including the Borneo region of Indonesia (10˚N–15˚S; 90˚–120˚W) [8]. **Figure 1** shows the location of the Borneo Vortex (BV) study in the western Indonesian Maritime Continent. The red box is denoted as the BV domain area.

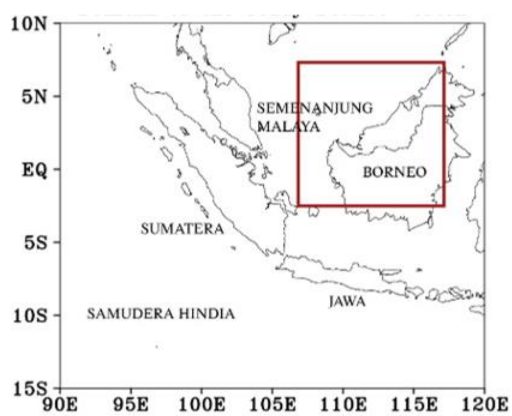

Figure 1. Location of the Borneo Vortex (BV) study in the western Indonesian Maritime Continent. The red box is denoted as the BV domain area

During the boreal winter, Borneo, Peninsula Malaysia, Sumatra, and other major islands of Indonesia experience the most active deep cumulus convective and highest precipitation. Latent heat release in this area is part of the Maritime Continental heat source, vital in various large-scale processes across the globe and region. A significant source of systematic errors over the tropical Indian and Pacific Oceans, as well as North America and extratropical northeastern

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Europe, was found in a study of atmospheric general circulation models by [9], who reached the conclusion that the Continental Maritime plays an essential role in the global circulation and emphasized that convective activity in this region with complex land-sea topography should be better represented. The region is surrounded by various topographic characteristics with different orientations, each of which can affect the distribution of deep convective systems. In addition, the area is highly susceptible to large-scale disturbances, whose variations propagate over long periods.

Previous studies have indicated that synoptic spatial-scale disturbances such as the BV typically persist for a few days to a week, largely due to its relatively steady characteristics [10]. This studies also suggest that variations in the BV life cycle can influence convective activity over the SCS. However, limited attention has been given to prolonged BV events that are not associated with cold surges, particularly in terms of their impact on convection over the Indonesian region.

In March 2023, an atypically long-lived BV event was observed, lasting approximately nine days. This case presents a unique opportunity to investigate the characteristics and impacts of a sustained BV episode independent of cold surges. This study aims to analyze the March 2023 BV event and its influence on convective activity over Indonesia. Section 2 provides an explanation of the data and methods used. Section 3 details the results of our study and our discussion. This includes thorough data analysis and our findings during our observation of the BV and its associated convective patterns. Section 4 provides the conclusion of the study as a whole. Previous studies stated that synoptic spatial-scale disturbances can last from a few days to a week due to the unchanging tendency of the BV [10]. However, there has been no study of the BV, which is not influenced by cold surges but has a long-lived cycle and influences convective activity in Indonesia.

Materials and Methods

The primary data used in this study are wind component (u,v), relative vorticity, specific humidity, vertical wind, Outgoing Longwave Radiation (OLR), Sea Surface Temperature (SST), and Cloud Liquid Water Content (CLWC) obtained from the European Re-Analysis (ERA5). Precipitation data were obtained from the Global Satellite Measurement of Precipitation (GSMaP). All datasets are available at a temporal and spatial resolution of every one hour and $0.25^\circ \times 0.25^\circ$. In this study, the BV is classified into three phases, namely: precondition of BV (pre-BV) on February 25–March 1, 2023, during BV on March 2–10, 2023, and postcondition of BV (post-BV) on March 11–15, 2023 using the composite method. The main BV phase was determined by examining the daily evolution of low-level winds fields, which clearly showed the formation intensification, and persistence of a cyclonic circulation over Borneo during March 2–10, 2023. The five-day periods before and after were selected to evaluate atmospheric changes associated with the BV's oneset and dissipation.

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Results and Discussion

The large islands of the Maritime Continent experience large-scale convective activity during the northern hemisphere winter. The highest convective activity occurs over Java, which connects with convective activity over Sumatra and moves eastward into the Indian Ocean as part of the Intertropical Convergence Zone (ITCZ) south of the equator [10]. Due to the blockage and deflection by the topography of Malaysia and Sumatra, the low-level northeast winds extending southward from the SCS are deflected westward and southward. In the northern part of the region, the westward deflection produces winds from the north that cross the equator and turn eastward near latitudes south of the equator. In the south, the deflection produces winds from the north that cross the Bay of Bengal. This counterclockwise rotation of the winds at 925 hPa pressure is due to vorticity and topographic deflection [11].

Through the composite map generated by utilizing the wind and relative vorticity data, it is clear that the relative vorticity covers most of Indonesia's Java, South Sumatra, and the north coast of Java. This is seen in **Figure 2a**, where the relative vorticity observed along the islands of the north coast of Java is shown in blue. This relative vorticity pattern indicates that the precipitation conditions or convective activity that occurred before the BV emerged was extensive. This suggests that the precursory effects of the BV are widespread.

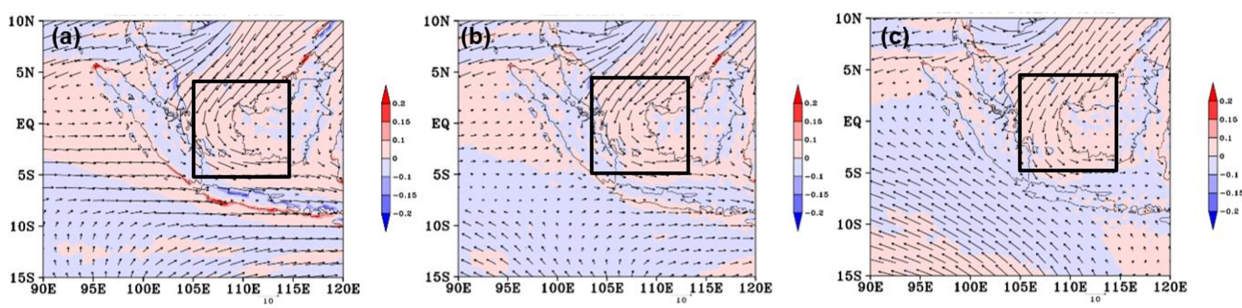

Figure 2. Composite map of wind and relative vorticity in the (a) pre-BV, (b) BV, and (c) post-BV phases. The BV center is most distinct in (b), showen by closed wind circulation over the northern Borneo

However, changes occur during active BV and post-BV conditions. The vorticity that initially covered the area began to decrease. The decrease in vorticity during active BV and post-BV shows that BV has changed the vorticity pattern of the area, indicating that the atmospheric dynamics have changed.

Under pre-BV conditions, convective activity connects precipitation and clouds through three discernible pathways initiating from the SCS and heading towards Borneo (**Figure 3a**). The first pathway went southward through the Java Sea, and the second toward the Malacca. These pathways are geographically important areas for convective activity and have links to pre-BV conditions. Previous studies have shown that these areas are prone to pre-BV conditions. Convective activity in these pathways plays a vital role in initiating the formation process of the BV. Since Borneo is often the main center of the BV, the first path towards Borneo has a significant influence. This organized convective structure, forming as a narrow and elongated band of clouds and precipitation, resembles a squall line–a mesoscale convective feature commonly associated with intense thunderstorms and strong vertical motion.

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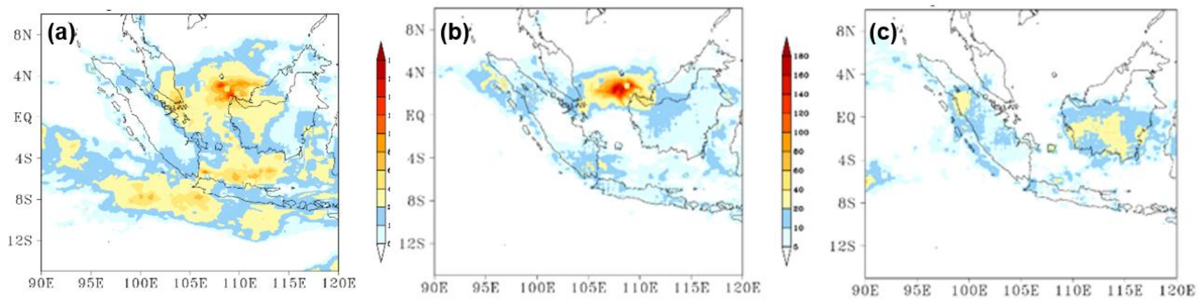

Figure 3. (a-c) Same as Figure 2, but for daily composite maps of precipitation averaged from hourly GSMaP data

The precipitation distribution pattern significantly changes during active BV (**Figure 3b**). Precipitation flowing south through the three previously mentioned pathways was stopped and concentrated around Borneo and Malaysia. Java Island also still experiences the influence of these precipitations, but the intensity has been reduced. The precipitations that may have occurred over Java Island at a stage before the BV formed now only remain remnants of previous convective activity. This process is due to the strong influence of the BV, which reduces the precipitation previously scattered across the Java Sea. The particular circulation pattern created by the BV diverted the wind flow and convection to the Kalimantan region and beyond area. As a result, the precipitation previously spread over the three main convective paths is now more concentrated in the region directly affected by the BV activity.

The change in precipitation distribution does not immediately disappear during the post-BV phase (**Figure 3c**). Although the SCS region that used to be the center of convective activity no longer experiences precipitation, no more vortices occur. However, precipitation still occurs in Kalimantan. After the BV phase, precipitation continued to fall over Kalimantan, indicating that the BV effect did not stop. The BV-activated convective system has a longer-lasting impact than the signal and direct effects of the BV. In other words, although the BV may no longer exist, its influence on convection patterns is still felt. This suggests that the BV affects not only the weather when it occurs but also convective activity after its phase has ended.

Northeast winds are stronger in winter than fall, but the air is colder and drier [12], [13]. SSTs are significantly lower in the northern and central parts of the SCS. Therefore, convective activity will not occur on a large scale until the air reaches the southern part of the SCS after being transformed by considerable surface heat, such as latent and turbulent heat [12]. This can be seen in **Figure 4** under pre-BV conditions (**Figure 4a**); the pattern of extensive convective cloud distribution in precipitation areas shows low OLR values. Low OLR values indicate thick clouds, which are often associated with thunderstorms, heavy precipitation, or other extreme convective activity. This suggests that moisture accumulation and convection occur in certain areas at the pre-BV stage, an essential component in BV formation.

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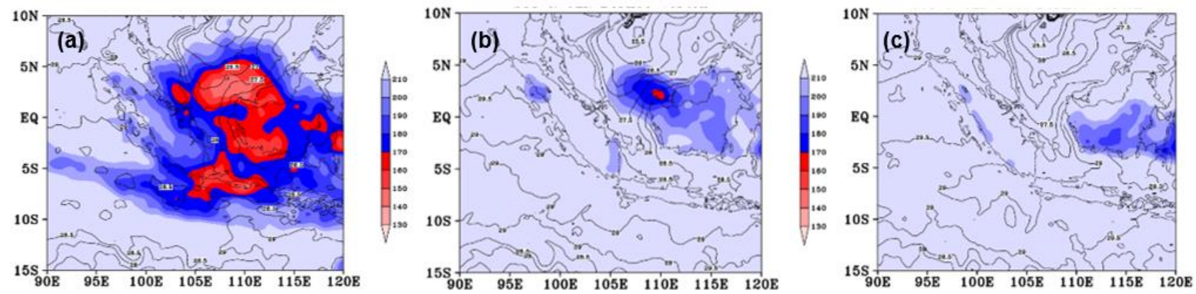

Figure 4. (a-c) Same as Figure 2, but for composite maps of Sea Surface Temperature (STT) and Outgoing Longwave Radiation (OLR) data

If we look at the SST values under pre-BV conditions, we will see an increase in SST in the SCS region. This increase follows a significant expansion of convective activity in SST. This suggests that sea surface warming is vital in promoting and maintaining intense convective activity in the region. In other words, the increase in sea surface temperature causes convective clouds and severe weather to develop. However, the SST of the pre-BV phase drops by 0.5° entering the BV phase. A more focused convective cloud pattern shows its impact. Convective clouds were initially widespread over the SCS and Kalimantan Island. This suggests that the redistribution of convective activity during the formation of the BV is also affected by SST changes. In the post-BV phase, the remnants of the convective clouds were only in parts of Kalimantan Island, and the SST values in this phase remained the same.

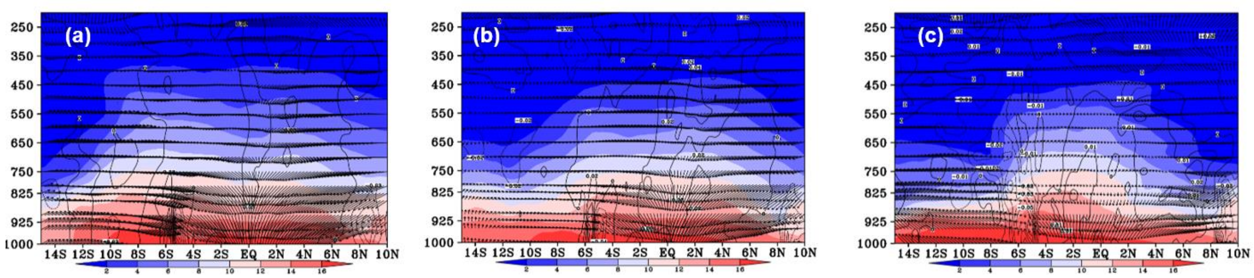

Figure 5. (a-c) Same as Figure 2, for the latitude-altitude Hovmoller composite of wind, specific humidity, and relative vorticity data

In addition, as shown earlier, in the pre-BV phase (**Figure 5a**), convective activity is more substantial and widespread. This stronger downdraft condition is part of the convective dynamics in the atmosphere related to the downward movement of air masses amidst the developing clouds. However, in the BV phase (**Figure 5b**), this strong downdraft is only concentrated in the SCS region. The downdraft has decreased, as it did in the post-BV phase (**Figure 5c**). This change in the downdraft pattern shows that the BV phase strongly influences the convective dynamics. The pre-BV phase is characterized by intense and widespread convection, and there are many downdrafts in the southern region due to changes in the air mass flow in the atmosphere at that time.

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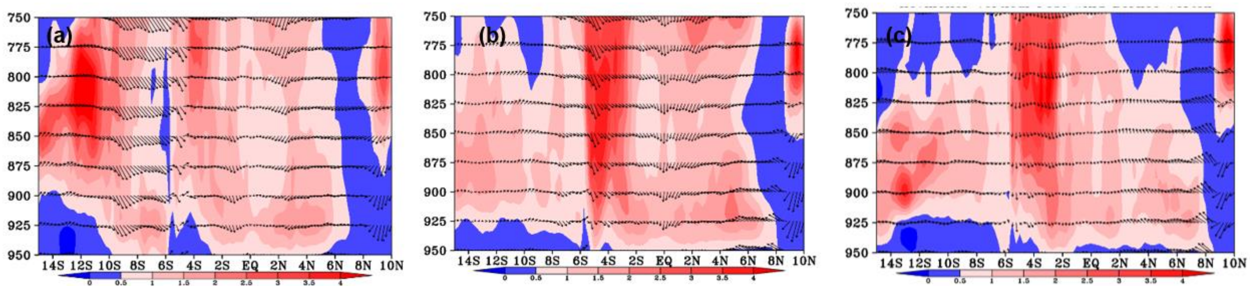

Figure 6. (a–c) Same as Figure 5, but for the latitude-altitude Hovmoller composite of Cloud Liquid Water Content (CLWC) and vertical wind data

In addition, it should be noted that Cloud Liquid Water Content (CLWC) plays a role in the dynamics of BV formation. In the pre-BV phase (**Figure 6a**), the cloud liquid water content in the southern region helps to increase the concentration of convective clouds in the SCS region and beyond when the BV occurs (**Figure 6b**) and continues until the final phase of the BV. This helps us understand the complex relationship between atmospheric conditions, sea surface temperature, and cloud patterns during the life cycle of the BV.

Conclusions

The long-lived BV case study was investigated in March 2023 using reanalysis data of ERA5 and GSMaP based on composite analysis. During the precondition of the BV (pre-BV) phase, convective activity increases significantly through three pathways: the island of Borneo, the Java Sea, and the Malacca Strait. This process was triggered by widespread convergence in the SCS, which was supported by a rise in sea surface temperature in the central SCS to 28°C. During the active BV, significant precipitation enhancement is concentrated over the SCS, while precipitation over the mainland decreases, which is supported by forming a downdraft over the Java Sea. During the postcondition of BV, a squall line pattern developed over the Java Sea, and precipitation increased over most of Kalimantan and western Sumatra. By combining these results, this study has shed light on the complex dynamics of the BV phenomenon and how it impacts precipitation and weather disturbance in the Indonesia Maritime Continent. 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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Yulihastin. Syifa Alifia Azzahra, Erma Yulihastin, and Eka Putri Wulandari are the main contributors to this manuscript, whereas others were supportive contributors.

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