Analysis of Vortex Development over Eastern Indian Ocean using Potential Vorticity

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Abstract. A vortex phenomenon may have a significant influence, especially on wind circulation patterns and extreme weather in Indonesia. The formation of the vortex, initially located over the eastern part of the Indian Ocean has drawn attention due to the highest frequency of its occurrence and as the source of the vortex over the Indonesian region. Vortices generated in this region is also suspected as one of contributing factor for flooding events at Jakarta in 2002 and 2007, studying both formation and development mechanism of these vortices is essential. The evolution of vortex development is investigated to characterize the vortex motion and development pattern in the Eastern Indian Ocean region. The study was conducted for 17 years starting from 1998 to 2016 on every December-January-February (DJF) period using ECMWF (European Center for Medium-Range Weather Forecast) ERA-Interim Reanalysis data. The analysis of vortex evolution was conducted for each event using a composite evolution of potential vorticity anomalies in the isentropic layer. The result shows 84 vortex systems identified with three characteristic patterns of vortex movement that occurred during 295 days of the observation period. Composite analysis of potential vorticity anomalies shows that the initial formation of vortices in the Eastern Indian Ocean is related to the emergence of negative potential vorticity anomalies from the west, which subsequently forming the vortices.

Keywords: Vortex formation, vortex characteristics, potential vorticity anomalies, Eastern Indian Ocean.

1. Introduction

Indonesia's geographic location causes the region to have many phenomena. A phenomenon that is a quite significant influence on wind circulation in Indonesia is a vortex event. The vortex can also cause weather disturbances such as rainstorms, windstorms or even develop into cyclones [1]. One of the low-level vortex phenomena that are often studied in Indonesia is the Borneo Vortex. Meanwhile, there is a low-level vortex whose occurrence frequency is quite significant compared to other areas in the
Indonesian Maritime Continent, namely the vortex in the Eastern Indian Ocean, especially in December-January-February (DJF). This vortex is suspected as one of contributing factors for flooding events in Jakarta in 2007 [2]. This vortex also plays a role in developing tropical cyclones in the Indian Ocean [3]. Hence both the formation and development of this vortex are essential to study.

Low-level vortex formation is associated with blocking by topographical features [4,5] and the effect of vorticity anomalies in the upper troposphere that move towards the surface [6]. Analysis of the formation mechanism and characteristics of this vortex can be explained by potential vorticity. Analysis of potential vorticity is quite widely practiced to study atmospheric phenomena such as the diagnosis of cyclone development and movement. Analysis of potential vorticity can explain the evolution and dynamics of upper and lower levels atmosphere [7]. Information about atmospheric conditions using potential vorticity is more detailed than analysis using pressure maps or stream functions [8]. Analysis of vortex formation using potential vorticity has also been carried out previously to study the mechanism related to the Borneo vortex in the Northern Hemisphere (NH) is explained [9].

Therefore, further analysis will be made regarding the characteristics of the emergence of vortices in the Southern Hemisphere (SH), especially in the Eastern Indian Ocean, and analysis of the evolution and strengthening of these vortices through potential vorticity parameters based on the characteristics obtained.

2. Data and Methods

The data used in this study is ECMWF (European Center for Medium-Range Weather Forecast) ERA-Interim reanalysis data, every six hour data (00 UTC, 6 UTC, 12 UTC, 18 UTC) with a spatial resolution of 0.25° × 0.25°. The data used every December-January-February (DJF) 1998/1999 to 2015/2016 (18 DJF periods data). For vortex identification, zonal wind and meridional wind data were used at the level of 925 hPa. Meanwhile, zonal wind, meridional wind, and temperature data were used to calculate the potential vorticity at 17 pressure levels (1000 hPa to 450 hPa). At the phenomena analysis, Sea Surface Temperature (SST) data from surface dataset ECMWF ERA-Interim reanalysis data were also used.

A vortex is identified when wind circulation on 925 hPa in the study area shows a clockwise circulation (at SH) with wind speeds exceeding two m/s in 2.5° × 2.5° square grid from the center of the circulation is located following a study by Chang et al. [10]. After determining the vortex using a streamline based on previous research, the relative vorticity value will also be analyzed on those days when the vortex was identified in the previous method to increase objectivity in identifying phenomena. Vortices in the Southern Hemisphere are identified when relative vorticity is less than -4 x 10^{-5} s^{-1} at the center of the vortex. The vortex identification study area in this study includes the Eastern Indian Ocean with coordinates 0°-15° S and 90°-105° E (figure 1).

The potential vorticity was calculated at the isentropic level. At the same time, the data used are pressure level data. So that each component must be interpolated in the isentropic level first to calculate the potential vorticity. In this study, the interpolation method used is linear interpolation. Furthermore, the calculation of potential vorticity refers to the following equation:

\[ P_V = -g \zeta_a \left( \frac{\partial \theta}{\partial p} \right) \]  \hspace{1cm} (1)

where,

\[ \zeta_a = \zeta + f \]  \hspace{1cm} (2)

\( PV \) is the potential vorticity of isentropic coordinates, \( g \) is the acceleration due to gravity, \( \zeta_a \) is the absolute vorticity, \( \theta \) is the potential temperature, \( \zeta \) is the relative vorticity; where \( \zeta = \left( \frac{\partial v}{\partial y} - \frac{\partial u}{\partial x} \right) \), and \( f \) is coriolis parameter [11]. Potential vorticity analysis was performed by calculating the anomaly and composite value of potential vorticity anomalies in vortex events. The value of potential vorticity anomalies is calculated by subtracting the value of potential vorticity with the average seasonal value of potential vorticity. Further analysis was performed for all vortex systems through a composite anomaly.
of vortex event. The composite method is carried out by averaging the vortex event based on the center of the vortex for each identified system (i.e., vortex with one lifetime) classification, with a radius given 15° or about 1650 kilometers on each side of the center of the vortex.

In this study, the analysis is done on the 302 K isentropic layer because the vortex is mainly located at a lower level, and the vortex identification process is also carried out at the lower level about 925 hPa. An analysis is also carried out in the middle troposphere at the isentropic level, which can explain the pressure level of 500 hPa or the 328 K layer. The concept of potential vorticity relates the dynamic processes of the upper level (middle troposphere in the tropics) to processes at the lower level or vice versa [8]. Hence, this research is carried out at those levels. The analysis was carried out to see the evolution and strengthening of the vortex for each characteristic of the vortex obtained.

![Figure 1](image-url)

*Figure 1.* The vortex identification area is marked with a red box (0°-15° S and 90°-105°E)

### 3. Results

#### 3.1. Identification of vortex

The vortex identification process results in a total of 84 vortex systems occurred in 295 days during the period of analysis (Table 1). The day of vortex event in the Eastern Indian Ocean reached 18.15% of the study period. The average lifespan of a vortex system that occurs ranges from 1-11 days, with three patterns of vortex direction of motion: stationary (not moving), moving west, and moving east. Stationary vortex (not moving) tend to have a relatively shorter life span than the vortices that move westward and eastward.

| Vortex motion   | Vortex event (day) | Number of vortex systems | System lifespan (day) |
|-----------------|--------------------|--------------------------|-----------------------|
| West            | 129                | 25                       | 3-11                  |
| East            | 94                 | 19                       | 4-9                   |
| Stationary      | 72                 | 40                       | 1-3                   |
| Total           | 295                | 84                       | 1-11                  |

Table 1. Vortex characteristics statistics for the period of DJF 1998/1999 to 2015/2016.
Figure 2 shows the spatial distribution of the 84 vortex systems in the Eastern Indian Ocean. The vortex center was determined using a closed circulation streamline and the most negative relative vorticity value. The distribution of each vortex system is relatively even in the study area. The moving vortex system tends to move southward.

![Figure 2. Spatial distribution of vortex system in the period of 1998/1999 to 2015/2016. The black dot shows the stationary center of the vortex, the red dot, and the red line show the vortex in an east direction (moves eastward), while the blue dot and dotted line show the center of the vortex system in a west direction (moves westward).](image)

3.2. Composite potential vorticity analysis of vortex evolution

3.2.1. Evolution of the vortex system moves westward

Analysis of the composite potential vorticity anomalies value will be carried out to see the beginning of forming the cyclonic pattern of this vortex system. In the composite of potential vorticity anomalies, it was seen that a few days before the event, there were strong negative potential vorticity anomalies in the south and west. Three days before the event (Figure 3b), the negative anomalies from the west began to move eastward.

A negative anomaly of potential vorticity got stronger and formed a cyclonic pattern that began to appear on the second day before the event. The negative potential vorticity anomalies advection from the west of the vortex system. Negative vorticity anomalies from the west remain connected to the vortex system and amplify the formation of its cyclonic pattern. On the day before the event (Figure 3d), the cyclonic pattern of the vortex system began to become clear compared to the previous day. The existence of a negative advection of potential vorticity anomalies from the west, which is getting stronger and it also strengthens the cyclonic pattern which is further identified as the vortex.
Figure 3. Composite evolution of potential vorticity anomalies as the system vortex moves westward in the 302 K layer in PVU (1PVU = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}) at (a) H-5 (b) H-3, (c) H-2, (d) H-1, (e) H-0, and (f) H+1

3.2.2. Evolution of the vortex system moves eastward

Figure 4 shows, the composite evolution of vortex events moved eastward. The evolution will be seen from five days before the event. From the results of the potential vorticity composite evolution, there are anomalous changes with time. In the days preceding the event, there was a strong negative potential vorticity anomaly in the southern and western parts of the vortex system center point. Three days before the event, the negative anomaly from the west began to move eastward. The negative potential vorticity anomalies got stronger and formed a cyclonic pattern that began to appear on the second day before the event.

Negative potential vorticity anomalies from the west remain connected to the system and amplify the formation of the cyclonic pattern. Meanwhile, the negative potential vorticity anomalies from the south are not directly connected to the vortex system because it is blocked by positive potential vorticity anomalies in the north. On the day of the event (Figure 4e), the maximum negative potential vorticity anomalies with a full cyclonic pattern have appeared in the center of the domain (about 0 km distance). The wind pattern also shows a cyclonic pattern. On the second day of the vortex formation (H + 1) shown in figure 4f, the vortex moved eastward.
3.2.3. Evolution of the stationary vortex system

In Figure 5, it can be seen that a few days before the event, there was a negative anomaly from the west moving eastward. This negative potential vorticity anomaly cause the advection of potential vorticity anomalies from the west, which strengthens until the day of the event (Figure 5e). The maximum negative potential vorticity anomalies and full cyclonic pattern indicates that vortices have formed, with the wind pattern also showing a cyclonic pattern. On the second day of formation of the vortex (H + 1), which is shown in figure 5f. The center of the vortex does not change which indicates that the vortex is stationary. The vortex system is no longer connected with negative potential vorticity anomalies from the west that causes stationary (not moving) vortices to have a relatively short lifespan.

Figure 4. As in figure 3, but for the vortex moved eastward
Potential vorticity anomalies can form either at the upper or lower levels or vice versa. Negative potential vorticity anomalies at the lower level tend to be stronger than the upper level so that the anomaly at the lower level is likely to affect the anomaly at the upper level.

From the vertical plot of potential vorticity anomalies shown in Figure 6, it can be seen that the disturbance originates from the lower level then affects the upper level so that at the upper level, a cycloic pattern is formed in the same area. The event of vortices over the Eastern Indian Ocean originated from the advection of negative potential vorticity anomalies from the west. The cycloic pattern that was formed was not due to the influence of the negative anomaly of upper-level potential vorticity.

Based on the identification results of the vortex phenomenon, stationary vortices with a fixed direction of motion (not moving) tend to have a relatively short lifespan of 1-3 days compared to vortices with the west direction of motion that have a system life of 3-11 days, and the vortex in an east direction has a system life of 4-9 days.
Figure 6. Composite vertical plot of potential vorticity anomalies in PVU (1PVU) = $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$) on (a) H-0; (b) H+1; (c) H+2 moves to the west, (d) H-0; (e) H+1; (f) H+2 moves to the east, (g) H-0; (h) H+1; (i) H+2 stationary vortex.

The vertical plot in Figure 6 shows that on the three days, the vortex occurrence in the system that moving eastward and westward are still connected with the negative potential vorticity anomalies from the west. Whereas in the stationary vortex system, the negative anomaly value of potential vorticity tends to be weaker. On the second and third day of vortex events, the vortex system is no longer connected with negative potential vorticity anomalies from the west. The moving vortex system is getting more robust due to the strengthening of the negative potential vorticity anomalies from the west, which causes the vortex system's lifespan to be longer than the stationary vortices, however based on the vertical plot, it is not known the cause of the movement of this vortex.

4. Discussion

4.1. Analysis of vortex system movement based on Sea Surface Temperature (SST)
Figure 7 shows the composite anomaly Sea Surface Temperature (SST) of vortex events for a vortex system moving eastward, westward, and stationary or fixed vortex. The vortex is shown by wind vector with a cyclonic pattern. Based on the interpretation of the figure, it can be seen that the vortex system tends to follow positive SST anomalies. The evolution of the vortex movement on the first day, the second day, to the third day of the vortex shows that the vortex tends to move towards positive SST anomalies.

![Figure 7: SST anomaly analysis of vortex movement on (a) H-0; (b)H+1;(c) H+2 moved westward, (d) H-0; (e)H+1;(f) H+2 moved eastward, (g) H-0; (h)H+1;(i) H+2 stationary vortex.](image)

Based on the interpretation of the figure, it can be seen that in the vortex system that moved westward, SST positive anomaly is in the south and southeast of the vortex center. Whereas in the vortex system that moved eastward, the SST positive anomaly is in the east and southwest of the vortex center. So that the vortex also moves to follow the positive SST anomaly. For the stationary vortex, the center of the vortex is in a positive SST anomaly.
4.2. Identification of Jakarta floods 2007 based on potential vorticity analysis

The case study of the vortex is one of the triggers for the 2007 Jakarta flood [2]. Vortex can affect wind circulation, especially meridional wind which is associated with the increased cross-equatorial flow. Based on Figure 8, it can be seen that the negative potential vorticity anomalies on January 29, 2007 (Figure 8a) were formed in the west to the east. The negative anomaly started to strengthen until it formed a cyclonic pattern on January 31, 2007, which was indicated as the initial formation of the vortex. The cyclone pattern associated with the negative anomaly reached the maximum anomaly value or the most negative potential vorticity anomalies on February 1, 2007 (Figure 8d).

Figure 8. Evolution of potential vorticity anomalies at 302 K layer in PVU (1PVU = 10^{-6} m^2 s^{-1} K kg^{-1}) during Jakarta floods, (a) 29 January 2007, (b) 30 January 2007, (c) 31 January 2007, (d) February 01 2007, (e) February 02 2007, and (f) 03 February 2007

Negative potential vorticity anomalies in the vortex system are not directly related to potential negative vorticity anomalies in the southern part of Sumatra and Jakarta. Potential vorticity at lower
levels can be formed due to heating or topographic effects [6]. The negative anomaly in the Jakarta area is amplified due to the strengthening of meridional winds that interact with the topographical area of Jakarta. Negative potential vorticity anomalies in the Southern Hemisphere (SH) are related to atmospheric stability and are associated with convection regions [8]. Based on the analysis of potential vorticity shown in Figure 8, the atmospheric instability in the Jakarta area that triggers flood events is related to an increase in meridional winds from the north, not due to the vortex system in the Eastern Indian Ocean.

5. Conclusions

Based on the identification of vortex events, it was found that the vortices over the Eastern Indian Ocean tended to move. There are three characteristics of the movement of the vortex system in the Eastern Indian Ocean, namely the vortex system that tends to move westward, the vortex system moved eastward, and the vortex system, which is relatively fixed or stationary.

From the analysis of potential vorticity anomalies on each characteristic of vortex movement, it shows that the vortex event is associated with negative potential vorticity anomalies from the west and is advected eastward. The advection of negative potential vorticity anomalies from the west causes the formation of negative potential vorticity anomalies, and the strengthening of the anomalies becomes increasingly hostile to form a cyclonic pattern which is subsequently identified as vortices. Reinforcement of the vortex from advection of negative potential vorticity anomalies from the west causes the vortex lifespan to be longer.

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References

[1] Hou J, Wang P and Zhuang S 2017 J. Atmos. Ocean. Technol. 34 101–15
[2] Pratama, B E 2014 Study of Vortex Activity over Indonesian Maritime Continent (Bandung: Digilib Institut Teknologi Bandung) https://digilib.itb.ac.id/index.php/gdl/view/15141 in Indonesia
[3] Wang C C, Ma S K and Johnson R H 2020 Mon. Weather Rev. 148 2777–99
[4] Fine C M, Johnson R H, Ciesielski P E and Taft R K 2016 Mon. Weather Rev. 144 4827–47
[5] Chang C P, Liu C H and Kuo H C 2003 Geophys. Res. Lett. 30 10–3
[6] Hoskins B J, McIntyre M E and Robertson A W 2007 Q. J. R. Meteorol. Soc. 111 877–946
[7] Wu L and Wang B 2000 Mon. Weather Rev. 128 1899–911
[8] Seo K H and Song E J 2012 Mon. Weather Rev. 140 1748–60
[9] Andarini D F 2013 Cold Surge and Borneo Vortex Analysis Using Potential Vorticity (Bandung: Digilib Institut Teknologi Bandung) https://digilib.itb.ac.id/index.php/gdl/view/2003 in Indonesia
[10] Chang C P, Harr P A and Chen H J 2005 Mon. Weather Rev. 133 489–503
[11] Holton J R and Hakim G J 2013 An introduction to dynamic meteorology: Fifth edition (Elsevier Inc.) pp 99-108