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The vertical and horizontal structure on the first intensification of tropical cyclone Seroja

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सार– इंडोनेशिया के उष्णकटिबंधीय भूमध्यरेखीय क्षेत्र में स्थित होने के कारण उष्णकटिबंधीय चक्रवात (TC) काफी दुर्लभ हैं। आमतौर पर इंडोनेशिया जैसे निम्न अक्षांश क्षेत्र में चक्रवात जनन होता है जो उष्णकटिबंधीय चक्रवात (TC) चरण से पहले होता है, जहाँ समुद्र की सतह का तापमान काफी अधिक होता है और इसलिए निम्न दाब क्षेत्रों को प्रेरित करने के लिए अनुकूल होता है जिसका उष्णकटिबंधीय चक्रवात (TC) चरण के दौरान भी स्पष्ट रूप से सार्थक प्रभाव देखने को मिला। हालाँकि, कुछ उष्णकटिबंधीय चक्रवात जैसे 2001-2002 में उष्णकटिबंधीय चक्रवात (TC) वामेई और 2017 में उष्णकटिबंधीय चक्रवात (TC) सेम्पाका इंडोनेशिया क्षेत्र के बहुत करीब आए। इंडोनेशिया में हाल ही में उष्णकटिबंधीय चक्रवात, जिसका नाम TC सेरोजा है, इंडोनेशिया के बहुत करीब आया और 2021 में नुसा तेंगारा तिमुर टकराया। सेरोजा के लिए, यह प्रणाली अद्‌वितीय है क्योंकि यह भूमध्य रेखा के पास एक चक्रवाती जनन से शुरू हुई और पश्चिमी ऑस्ट्रेलिया में दूर तक फैल गई जो भूस्खलन से एक सप्ताह पहले तक बनी रही। उष्णकटिबंधीय चक्रवात को वर्गीकृत किया गया पहला तीव्रीकरण बस एक छोटा सा क्षण था, जो फिर समाप्त हो गया और फिर हिंद महासागर के ऊपर अपनी सबसे प्रबल तीव्रता तक पहुँच रहा है। इस शोधपत्र में TC सेरोजा का मूल्यांकन प्रणाली की विशेषताओं, पर्यावरणीय स्थिति और संरचना को समझने के लिए किया गया, विशेष रूप से TC के लिए जो निकट उष्णकटिबंधीय क्षेत्र में आया। प्रणाली की विशेषताओं को समझने के लिए ऊर्ध्वाधर संरचना के साथ-साथ क्षैतिज संरचना का भी मूल्यांकन किया जाता है। इस शोधपत्र से पता चलता है कि TC सेरोजा, जब इंडोनेशिया से टकराया तो एक विशिष्ट चक्रवाती जनन के साथ, विशेष रूप से वर्षा के कारण सबसे जबरदस्त प्रभाव पड़ा था। तीव्र पर्यावरणीय पवन कतरनी उन कारकों में से एक है जो TC सेरोजा को ऊर्ध्वाधर और क्षैतिज रूप से अद्‌वितीय बनाती है। इस शोधपत्र द्‌वारा, उष्णकटिबंधीय क्षेत्रों में TC चरण के दौरान जानकारी प्राप्त होने की उम्मीद है, इस प्रकार, विशेष रूप से उष्णकटिबंधीय क्षेत्र में न केवल परिपक्व या सबसे मजबूत तीव्रता के दौरान TC की विशेषताओं और संरचनाओं को स्वीकार किया जाता है, बल्कि पहले TC तीव्रीकरण चरण को भी स्वीकार किया जाता है।

ABSTRACT. Since Indonesia lies in the equatorial region, tropical cyclones (TC) are quite rare. The cyclogenesis phase which is prior to the TC stage usually takes place in the low latitude region like Indonesia, where the sea surface temperature is quite high and hence favourable to induce low-pressure areas, apparently giving a meaningful impact as well as during the TC stage. However, some tropical cyclones ever occurred very close to the Indonesia region such as TC Vamei in 2001-2002 and TC Cempaka in 2017. The most recent tropical cyclone in Indonesia, namely TC Seroja, occurred very close to Indonesia and hit Nusa Tenggara Timur in 2021. For Seroja itself, the system tends to be unique because it started from a cyclogenesis stage near the equator line and dissipated far in western Australia which survived more than one week before landfall. The first intensification that was categorized into a TC was just a short moment, which then dissipated & intensified again reaching its strongest intensity over the Indian Ocean. TC Seroja was evaluated in this paper to understand the system characteristics, environmental condition & structure, especially for TC that took place in the near tropical area. The vertical structure is evaluated as well as the horizontal structure to understand the characteristics of the system. This paper revealed that the TC Seroja, with a typical cyclogenesis phase when it struck Indonesia, had the most tremendous impact caused especially by precipitation. The strong environment wind shear is one of the factors that makes TC Seroja unique vertically and horizontally. By this paper, the information during the TC stage in the tropics is expected to be achieved, thus, not only the TC characteristics and structures during the mature or strongest intensity are acknowledged, but also the first TC intensification stage, especially in the tropical region.

Key words – Tropical Cyclone Seroja, Vertical structure, Horizontal structure.

1. Introduction

Since it lies in the tropical area, historically and theoretically, Indonesia the region where tropical cyclones very rarely occur due to near-zero Coriolis force in the tropics area (Gray, 1968), which will be discussed in more detail later on. However, in fact, two tropical cyclones ever happened near the Indonesia region before TC Seroja, namely Typhoon Vamei in 2001-2002 (Chang *et al.*, 2003) and TC Cempaka in 2017 (Winduprana *et al.*, 2019), which also caused much damage and destruction in infrastructure, livelihood, social-economic, etc. Several years after experiencing Typhoon Vamei, specifically in 2008, The Indonesian Agency for Meteorology, Climatology and Geophysics inaugurated the Tropical Cyclone Warning Centre (TCWC) Jakarta that covers the waters region from the Indian Ocean western of Southern Sumatra Island until the northern waters of Papua Province or among coordinates 90° - 125° E and 10° S - Equator. TCWC Jakarta is responsible for carrying out tropical cyclone monitoring including TC analysis and forecast, as well as giving the public warning if there were a situation to be considered as a TC or TC suspect over the region.

The tropical cyclone that has ever recorded passing Indonesian waters is triggered by different energy sources. Typhoon Vamei developed not from the mechanism already mentioned by Gray (1968), *i.e*., the warm ocean, yet drifted by a strong Borneo vortex during the boreal winter where the sea surface temperature should be cooler within the disturbance system (Chang, 2003). On the other hand, there is some evidence that proofs to the development of TC Cempaka were triggered by the environmental condition mentioned by Gray (1968). High sea surface temperature, an abundance of water vapour in the atmosphere, and unstable atmospheric environment conditions (Swarinoto *et al.*, 2019) drove the tropical system to become more and more significant even though lies in the tropics. Similar to Cempaka, tropical cyclone Seroja was also triggered by an ocean-warm condition during the end of boreal winter (Swarinoto *et al.*, 2019; Kurniawan *et al.*, 2021), where the sea surface temperature over the northern sea of Australia still serving as an energy source for tropical cyclones that initiate over the eastern Indonesian sea. This evidence aligns with a previous study, which revealed that cyclonic systems originating in the southern Indonesian seas typically move westward into the Indian Ocean, where they may dissipate near western Australia, or occasionally make landfall on the west coast of Australia (Dare and Davidson, 2004).

The impacts, for sure, are always different from the impacts faced in the mid-latitude region like Australia for the southern hemisphere basin or even the Philippines for the western Pacific basin. Even though Indonesia receives heavy rainfall, strong wind speed, rough sea over the coastal region as well as storm surges when there is a TC that is very close to Indonesia or even in Indonesia, the intensity should be weaker regarding the Coriolis reason that obstructs the severe cyclonic disturbance over equatorial region. We also construct some evidence to identify the impact caused by TC Seroja during the genesis and the tropical cyclone phase in Indonesia. Based on observation data from 7 (seven) BMKG meteorological stations around NTT province, heavy rainfall occurred on April 4th and 5th in Kupang City (figure not shown). which reached 306 mm/day and 333 mm/day (consecutively) proving that this tremendous event could break everything in the city. Even though it did not receive extreme rainfall instead of that happened in Kupang City, Rote Island, located about 95 kilometres southeast of the Seroja centre, experienced the strongest wind speed compared to other cities in NTT Province (figure not shown). Table 1 shows the tropical cyclone Seroja best track data obtained from the Bureau Meteorology of Australia (BoM), with the track map presented in Fig. 1

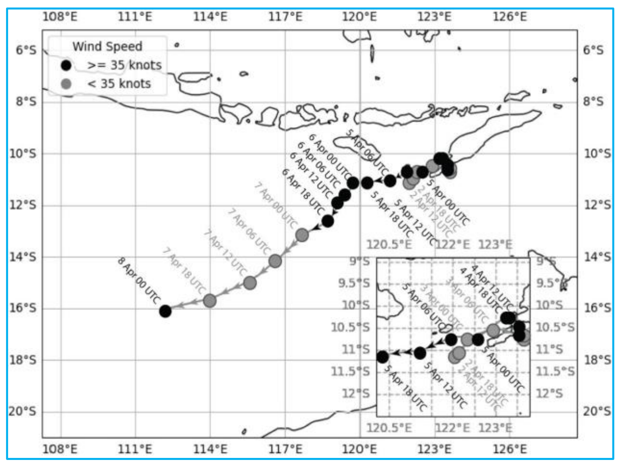

Fig. 1. The track map of Tropical Cyclone Seroja illustrates the information from the best track data presented in Table 1

Tropical cyclone Seroja that was started in Sawu Sea, Nusa Tenggara Timur and ended up in Australia gives a tremendous impact on many aspects of livelihood for the NTT Province. Before the tropical disturbance system reached tropical cyclone category, or when it was still in the genesis stage, the heavy rainfall with a remarkably strong wind already threatened about 14 regencies/cities in the province of East Nusa Tenggara (NTT) and even became more extreme and significant when it reached tropical cyclone stage. The National Disaster Management Agency reported about 124 people died, 74 people were lost, 129 were injured, and 12,230 people evacuated during the genesis stage up to when TC Seroja developed near NTT Province. It is because that tropical cyclone

Seroja brings several kinds of hydrometeorological disasters, *i.e*., floods, flash floods, landslides, strong wind, tremendous thunderstorms, and storm surges along the NTT coastlines during the pre-tropical cyclone, up to the mature phase of the tropical system near Rote Island.

There were several studies evaluating the impact of tropical cyclone Seroja, a few of them are the heavy rainfall impact on the province of NTT (Sekaranom *et al*., 2021), heavy rainfall and sea wave height in NTT (Kurniawan *et al*., 2021) and impact on phytoplankton chlorophyll-a and sea surface temperature in Savu Sea (Setiawan *et al*., 2021). The strategic planning to strengthen the early detection and tracking of tropical cyclones that possibly occur near or over Indonesian waters and may bring an extreme impact, as a lesson learned from the tropical cyclone Seroja event, had been designed by Makmur *et al*. (2021). Nevertheless, the more detailed structure and characteristics of tropical cyclone Seroja during the development phase, which can be atmospheric evidence and useful for further (likelihood of TC genesis genesis potential condition), are still not studied yet. Thus, to fill the gaps, the objective of this study is to synthesize the horizontal and vertical structure and characteristics of tropical cyclone Seroja from the genesis until the mature stage that eventually leaves the Indonesian water so that the forecaster's skill to do early detection of a tropical cyclone can be enhanced.

A previous study about the vertical structure of tropical cyclone rainbands was evaluated by Hence and Houze (2012) using TRMM precipitation radar, which revealed that the vertical structure in the inner region change with storm intensity, while no significant change in vertical structure in the outer region. Their work covers the Atlantic and Northwest Pacific basins between 1997-2007, where some tropical cyclones with unique vertical structures could be ignored because of the aggregation method. Hence, a deep analysis of a single tropical cyclone is necessary to carry out, to obtain a more reliable condition of a specific and unique structure and characteristic.

2. Data and methodology

The methodology used in this paper is quantitative-descriptive, where the dataset is treated to indicate system structure and characteristics through quantitative calculation from both mapping or plotting images. TC identification step was undertaken by identifying the system feature and structure vertically and horizontally. TC structure identification in this paper was identified by pattern during the development phase, where the steps being analyzed in this paper are from the system still in the genesis phase until the system reaches its maximum intensity, *i.e.*, from April 1st to April 7th 2023. Both the dissipation stage and landfall are not analyzed in this paper.

Several weather parameters being examined in this paper are circulation pattern, wind speed, wind shear, convergence/divergence, and vertical velocity (vv) around the system and its surrounding environment. The vertical velocity is an important parameter for the TC development stage because the upward and downward motion inside and outside TC systems are crucial in maintaining the system development and the eyewall formation and structure (Black *et al.*, 1996). The upward and downward motion can be examined using vertical velocity because of its ability to determine the deep convective mechanism (May and Rajopadyaya, 1998). Tao and Li (2014) revealed that vertical velocity also influences the moisture supply due to the latent heat released inside the thunderstorm body.

The average vertical velocity in the TC centre was calculated by averaging the vertical velocity between 0.73 degrees west and east. This calculation was performed to determine the vertical structure of upward and downward motion within the TC system. Saha (1968) mentioned in his paper that the vertical velocity equation (ω) in the pressure coordinates was written as follows:

$$\frac{\omega}{p} = -\nabla . v \tag{1}$$

where $\omega = \partial p / \partial t$, ∇ is the divergence operator, so that -∇. v is the divergence of horizontal velocity vector v, and p is pressure. The equation (eqn.1) states that the change of vertical velocity with pressure coordinate levels is equal to the negative divergence of the horizontal wind field. If the vertical velocity is integrated over a pressure level p_1, it will be written as,

$$\omega_1 = \omega_0 + (-\nabla . v)(p_0 - p_1) \tag{2}$$

where ω_1 is the vertical velocity at the top of the layer and ω_0 is the base of the layer where the vertical velocity started to be integrated.

The data used in this research is the daily reanalysis model from ERA-5 by the ECMWF due to its advance from being assimilated with a 4D-Var and model forecast in CY41R2 of ECMWF Integrated Forecast System (IFS) (refer to ECMWF documentation). Meanwhile, the TC Seroja track data was obtained from both the Jakarta Tropical Cyclone Warning Centre (TCWC) and the Australian Bureau of Meteorology (BoM) as the system had experienced cross - boundary official areas of

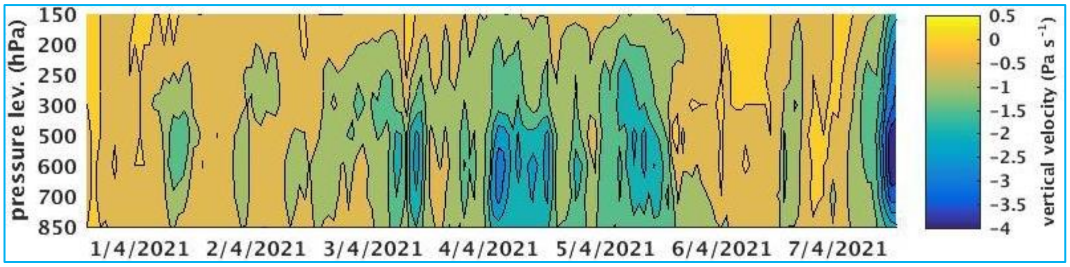

Fig. 2. Multi-level (850 to 150 hPa) vertical velocity from April 1st 2021, until April 7th 2021

monitoring responsibility. The duration of the dataset evaluated in this paper is limited from the genesis stage up to maximum intensity when the TC were over the Indian Ocean west of Australia region.

Since the data used in this research is ERA-5 from the European Centre for Medium-Range Weather Forecasts (ECMWF), it refers to the ECMWF documentation which mentions that the vertical velocity parameter is defined as the speed of air motion in the upward or downward direction. It uses a pressure-based vertical coordinate system and pressure decreases with height. Therefore, the negative vertical velocity represents an updraft in the atmosphere whereas the positive represents the downdraft over the atmosphere.

3. Results and discussion

Climatologically, tropical cyclone Seroja is an ordinary low disturbance system that occurred in the Indonesia region, primarily it lies in the Southern Hemisphere. There have been at least two tropical cyclones that crossed East Nusa Tenggara Province within 10 years, since 1982 (Figure not shown). As already mentioned in the methodology, the vertical velocity is utilized to identify the vertical motion of the system. Thus, the horizontal and vertical structure and characteristics of the system during each stage can be distinguished. Meanwhile, other meteorological parameters were also evaluated, such as divergence, wind speed and direction, including vertical wind shear. Convergence over the lower level and divergence over the upper level is needed to maintain tropical cyclone development, especially during Convective Instability of the Second Kind (CISK), when the system achieves its mature stage.

The time-pressure level diagram is presented in Fig. 2 to display a vertical velocity value. The vertical axis indicating the pressure level started from 850 hPa represents the lower level of the atmosphere and ends with 150 hPa, which represents the upper level of the atmosphere. Meanwhile, the horizontal axis indicates the time expected to figure out the system development day by day. Meanwhile, the vertical velocity value in each grid was calculated from the average between 0.73 degrees or about 81 kilometres east-west and north-south for each level and each time. The colorbar on the right side of the figure shows the vertical velocity value, where negative vertical velocity is indicated as blue, while positive is indicated as yellow. The lowest (strongest negative) vertical velocity started from -4, while the highest (strongest positive) ended at +0.5. It shows that the atmospheric condition during the early development stage until its maximum intensity mainly indicates updraft motion, thus, driving the system intensification strongly.

It shows that the vertical velocity became significantly negative from 850 - 200 hPa on April 3rd, 2021 about the evening just before the system reached the tropical cyclone category. This similar condition continue until early April 6th, when the vertical velocity value increased and became positive between the middle and upper levels in the atmosphere. This condition also corresponds to the TC track data from Table 1, where after the system passed its Tropical Cyclone category on April 4th at 00Z, weakening for a while, which started from April 7th at 00Z and finally intensified again on April 8th at 00Z. However, the vertical velocity becomes rapidly significant starting in late April 7th. It also revealed that the atmospheric level of negative vertical velocity that indicates a strong updraft motion inside the system is in the middle level of the atmosphere, around 700 to 400 hPa. The maximum vertical velocity in the middle level of the Tropical Cyclone is also in line with Frank and Ritchie (1998), where the maximum vertical velocity in the middle level of the Tropical Cyclone can achieve the sight of the convective processes and overall storm structure. The reason is that latent heat released from the condensation inside the system occurs in the middle level of a Tropical Cyclone to keep the system remain unstable. A strong updraft in the middle level indicates the transport of heat and moisture from the lower levels to higher altitudes.

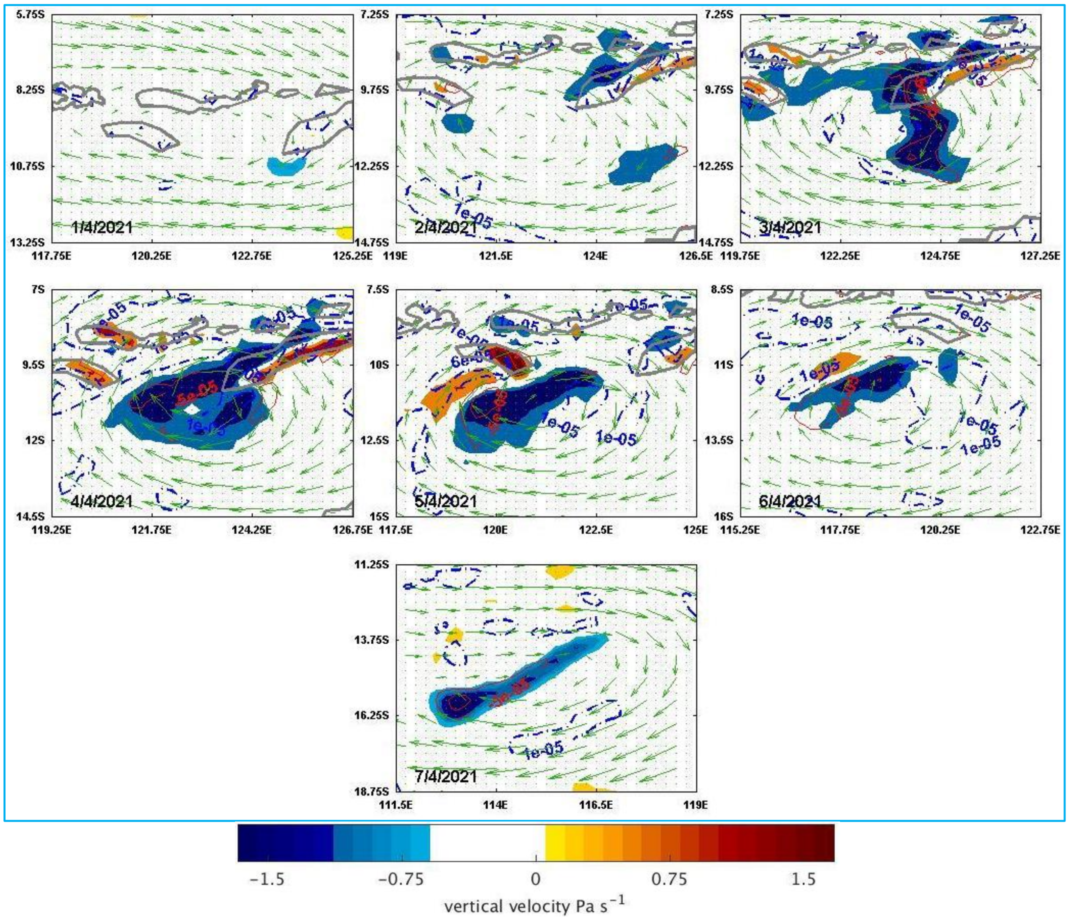

Fig. 3. Daily average vertical velocity superimposed with daily average wind vector at 850 hPa from April 1st, 2023 (upper-left) until April 7th 2023 (bottom)

The vertical velocity is also displayed in a horizontal map in Fig. 3, averaged daily from April 1st to April 7th 2023. The vertical velocity is displayed in shading, where blue shading is for negative value and orange shading is for positive value, as shown in the colour bar below the maps. It is then superimposed with 850 wind vectors in green arrow and superimposed with divergence in contour, where dashed blue for positive and red for negative represents the divergence and convergence respectively. An organized circulation wind has already formed since April 1st over the Sawu Sea, then became stronger the day after and slightly moved southward. The system remains in a similar location until April 4th. It then moved southwest quite faster, from April 5th until April 7th, where we limited the analysis. It is clear that during the genesis stage, the system kept stuck over the southern sea of East Nusa Tenggara Province or Nusa Tenggara Timur (NTT) while becoming Tropical Cyclone Seroja over a similar region within the next two days and moving fast southwestward and becoming a bit dispersed into disorganized wind feature. For the daily 850 hPa vertical velocity in the horizontal map, it can be seen that the updraft motion predominantly occurs over the northeast to southeast portion of the disturbance envelopes accompanied by the convergence on April 3rd. The updraft motion with convergence was also well performed for all portions on the next day and became narrower and concentrated over the west-to-north portion of the disturbance on the next two days. From the 6th to the 7th of April, the vertical velocity envelope becomes narrower along with its weakening stage, which is already shown in Table 1. However, the downdraft portion occurred in the nearest (left side or right side) of the updraft portion, which coincides with the divergence area inside it.

Fig. 4 also confirms Fig. 3, where the convective band predominantly wraps the updraft area around the disturbance, even though the convective band pattern does not exactly fit the negative vertical velocity shading pattern. There is a shifting position of the cyclone centre

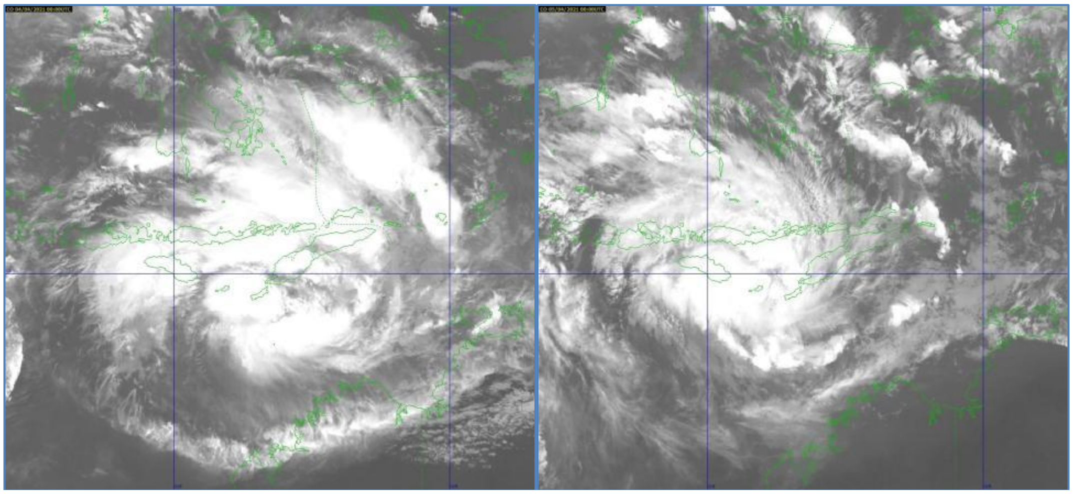

Fig. 4. Himawari Infrared (IR) Imagery on April 4th, 2021 at 0000 UTC (left) and on April 5th, 2021 at 0000 UTC (right)

TABLE 1

TC Seroja best track data obtained from Bureau Meteorology of Australia (BoM)

Year	Mon	Day	Hour UTC	Pos. Lat (S)	Pos. Long. E	Pos. Acc. nm	Max Wind (10 min kn)	Max gust kn	Cent. Press hPa
2021	4	2	12	11.1	122.1	45	20	45	1002
2021	4	2	18	11.0	122.2	45	25	45	1002
2021	4	3	0	10.7	122.4	45	25	45	1003
2021	4	3	6	10.5	123.0	45	25	45	1001
2021	4	3	12	10.7	123.7	45	30	45	1001
2021	4	3	18	10.6	123.7	15	30	45	997
2021	4	4	0	10.6	123.6	15	**35**	50	995
2021	4	4	6	10.4	123.6	30	**35**	50	995
2021	4	4	12	10.2	123.4	30	**35**	50	995
2021	4	4	18	10.2	123.3	30	**40**	55	990
2021	4	5	0	10.7	122.6	15	**45**	65	991
2021	4	5	6	10.7	122.0	20	**50**	70	987
2021	4	5	12	11.0	121.3	15	**50**	70	988
2021	4	5	18	11.1	120.4	20	**55**	75	985
2021	4	6	0	11.1	119.8	25	**60**	85	980
2021	4	6	6	11.6	119.5	20	**45**	65	988
2021	4	6	12	11.9	119.2	45	**40**	55	993
2021	4	6	18	12.6	118.8	45	**35**	50	997
2021	4	7	0	13.1	117.8	25	30	45	1000
2021	4	7	6	14.1	116.7	20	30	45	1000
2021	4	7	12	14.9	115.7	60	30	45	1000
2021	4	7	18	15.6	114.1	30	30	45	999
2021	4	8	0	16.0	112.3	30	**35**	50	994

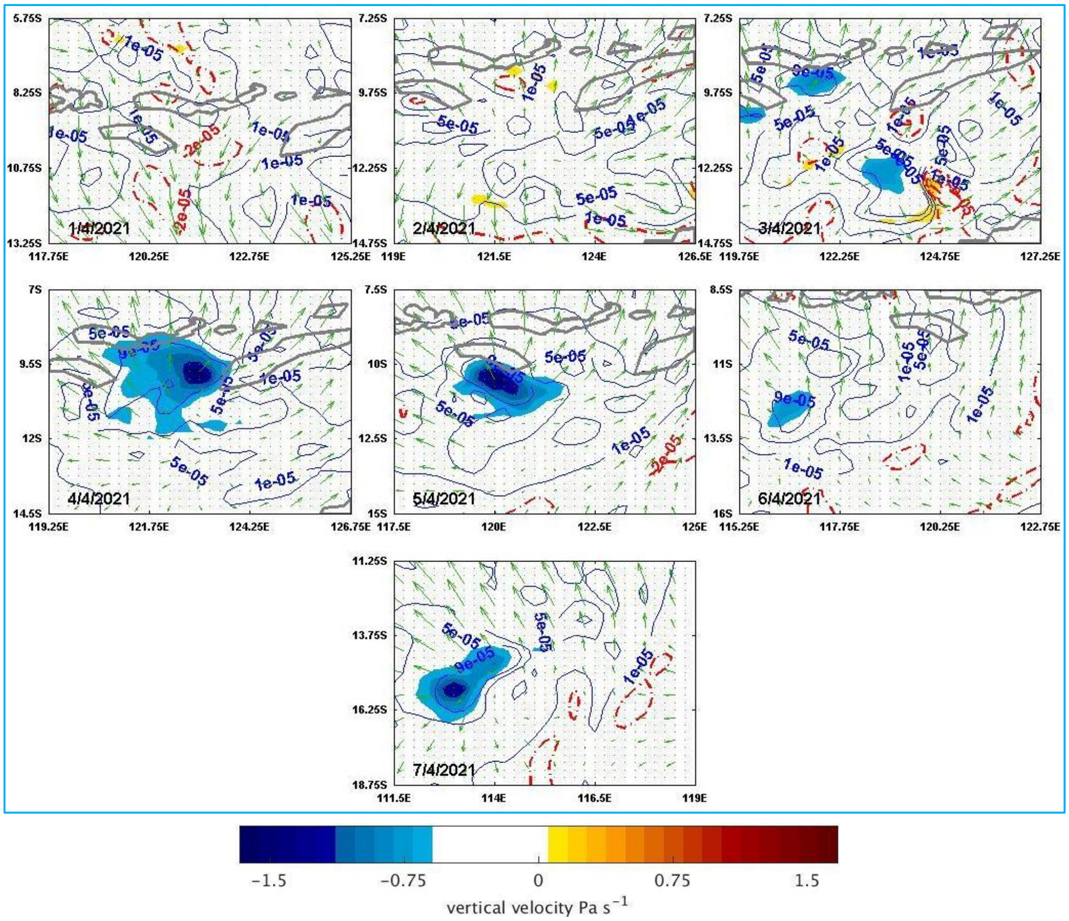

Fig. 5. Similar to Fig. 2 but for 150 hPa

shown between those figures, as well as a dry line over the southern coast of Timor Island that exhibits in Fig. 3 but shifted far southwest in Fig. 4. These differences are probably due to the level difference between the 850 hPa of reanalysis data in Fig. 3, with the Infrared (IR) satellite image in Fig. 4. Fig. 3 solely shows the atmospheric condition at the level of 850 hPa, where the satellite is the impact of what happens within the column of the atmosphere from the surface to the could top level and involves all weather parameters. However, the clear region without clouds that indicates a downdraft emerged narrowed along the east-southeast from the organized band also confirms the downdraft indicates a dry line over the southern coast of Timor Island in Fig. 3.

On the other hand, from the horizontal map in the upper level in Fig. 5, we can see that the outflow structure is exhibited from the wind direction from April 2nd until April 7th. Moreover, starting from April 3rd, the upper-level outflow obviously shown originated from that maximum updraft region (indicated by a dark blue shading). It means that the updraft still persists until the upper level around the system centre, although the outflow already formed as evidence of a strong Tropical Cyclone development stage. However, the divergence that coincides with the negative vertical velocity pattern near the TC's centre also indicates a strong outflow, which was already well-organized starting from April 3rd and became stronger on April 4th, although weakening on April 6th and became organized again on April 7th.

The vertical motion using vertical velocity and divergence data of each day was then evaluated to see the vertical structure of the system at each stage of development (Fig. 5). The vertical axis is for pressure level, and the horizontal axis is for longitude, where negative represents west and positive represents east. The vertical dashed grey line is for the system centre, where defined from the minimum pressure value at level 850 hPa. The vertical velocity indicates the shading area, where the maximum (positive) value is 0 and the minimum (negative) value is -1.8, which is the colour information presented on the colour bar below the images. The divergence is in contour, where red represents

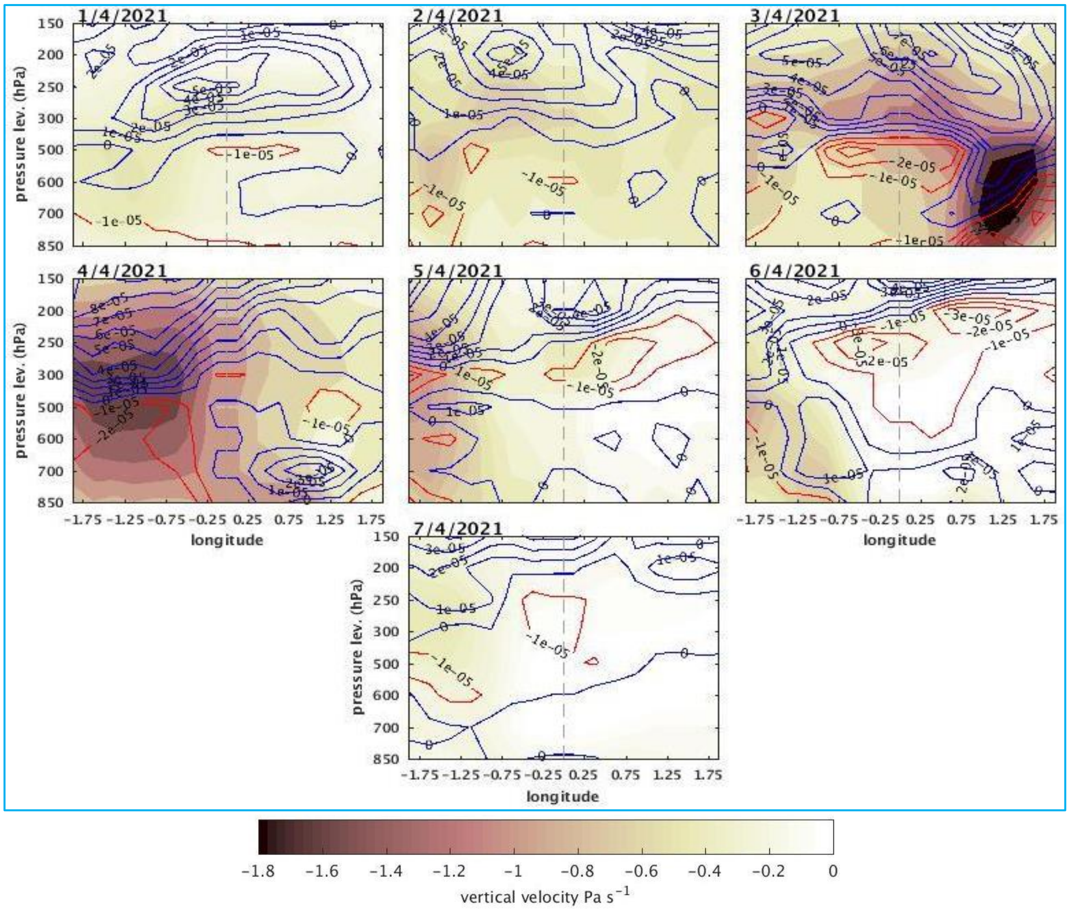

Fig. 6. Similar to Fig. 2, but for 850 to 150 hPa vertical velocity (brownish shading area) and divergence (red-blue contour) over the longitudinal coordinate along the system centre

convergence (negative value), and blue represents divergence (positive value).

Fig. 6 shows that there is an embedded atmospheric updraft shifting, especially on April 3rd, where the updraft motion was concentrated east of the system centre, then shifted west of the system centre the day after. This condition might appear because of the hourly and latitudinal average calculation to exhibit a vertical structure of the system. The vertical structure and characteristics look more disorganized between the vertical velocity shading pattern with divergence contour pattern during almost all the stages except on April 4th, where the lower to middle-level convergence corresponds with the updraft motion, which exists all along the vertical column in the system. A fading shade of negative vertical velocity that represents a weakening updraft accompanied by some convergence contour moved westward, away from the system centre from April 5th to April 6th, indicates a slow development step even shows a weakening tendency of tropical cyclone development just after it was identified as a Tropical Cyclone Seroja. It is presumably due to a strong environmental wind shear to the west that shifted and probably tilted the disturbance relative to the elevation westward quite far from the centre, as shown in Fig. 7.

Wind shear around the system was also plotted to show the environmental condition for embedded cloud and system development along the vertical column as shown in Fig. 7. The wind speed difference between 850 and 200 hPa was then daily averaged for each grid and categorized into three categories, *i.e.*, favourable when wind shear is less than and equal to 10 knots (green contour), unfavourable when wind shear is more than 20 knots (red), and neutral if in between (orange). The blue cross-circle icon on each map shows the system centre obtained from the minimum mean sea level pressure, where the direction of wind shear is also plotted and exhibited by the grey wind barb. Wind shear categories adopted from the Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin-Madison, denote the atmospheric conditions for tropical cyclone vertical development within the

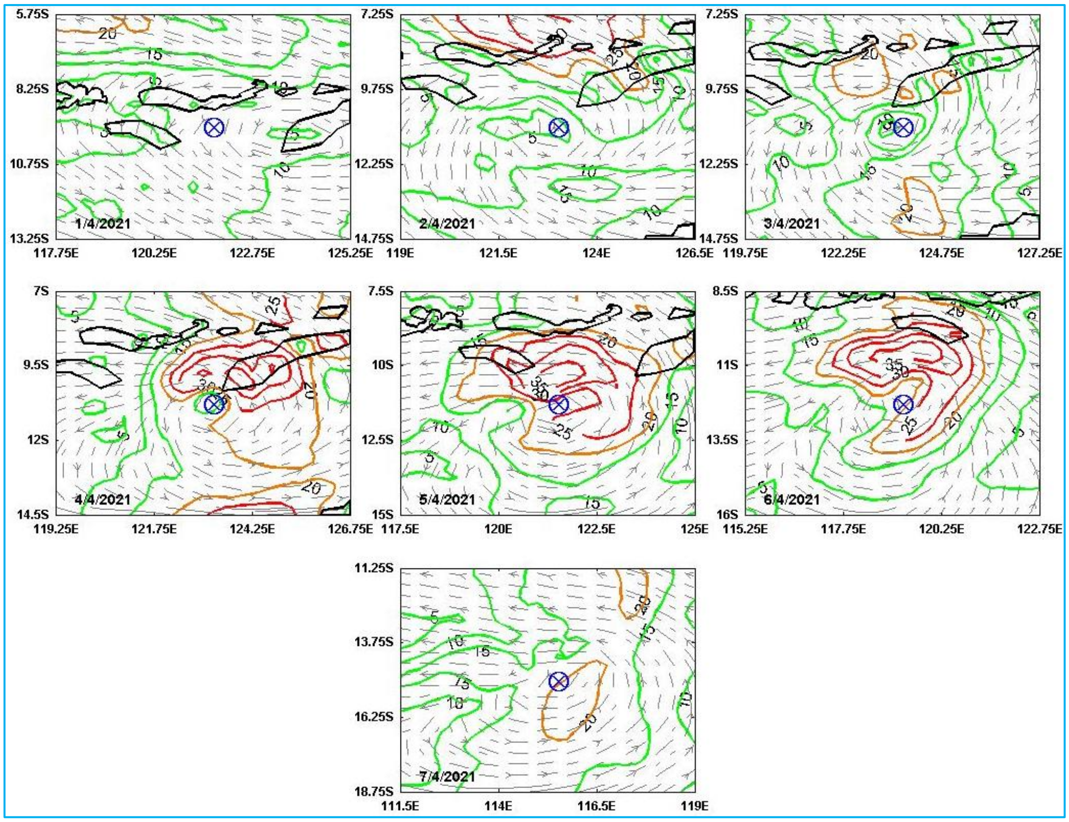

Fig. 7. Similar to Fig. 2, but for wind shear (calculated from 850 to 200 hPa wind difference) with a green contour for favourable, orange for neutral and red for unfavourable atmosphere, with a blue cross-circle icon showing the system centre

atmospheric column. The favourable category indicates the most ideal atmospheric condition, while the unfavourable could break up the system development in a vertical way. The shallowed clouds in the system centre with embedded clouds tilted away relative to the elevation is an example of a tropical cyclone with unfavourable wind shear, which eventually could weaken and dissipate the system.

Following The National Report for Tropical Cyclone Seroja from BMKG and BoM (as Seroja passed both Indonesia and Australia), the weakening of TC Seroja since April 6th was due to strong wind shear that persisted since April 4th at 00Z just after this system became a tropical cyclone category. This fact is also proven by Fig. 7, where a strong wind shear occurred on April 4th and became stronger on April 5th, followed by the dissipation of TC Seroja on April 7th. However, the strong wind shear started weakening on April 6th and more weakening on April 7th until it reintensified into a tropical cyclone category on April 8th as shown in Table 1. The strong wind shear on April 4th in Fig. 7 is also causing the wide spread of cloud bands toward the northeast and southeast side away from the centre shown in Fig. 4. This evidence is also in line with what has already been revealed by Sitkowski and Barnes (2009), that a stronger shear could decrease the size of the tropical cyclone's inner core with much less organized cloud bands and asymmetries convection.

The hourly maximum wind speed for each level from April 1st to April 7th was then plotted as in Fig. 8, where the maximum wind within the 95% confidence interval was also plotted to represent the more realistic value. The purplish shading shows the maximum wind shear for each grid and each level, calculated from the average between 0.73 degrees or about 81 kilometres within the quadrant (similar to Fig. 2). The horizontal axis is for time, the vertical is for the pressure level, the upper plot chart is for all ranges, and the bottom is for 95% confidence of maximum wind shear in knots.

In Fig. 8, we see that the maximum wind speed of the low level reached its strongest on April 5th afternoon

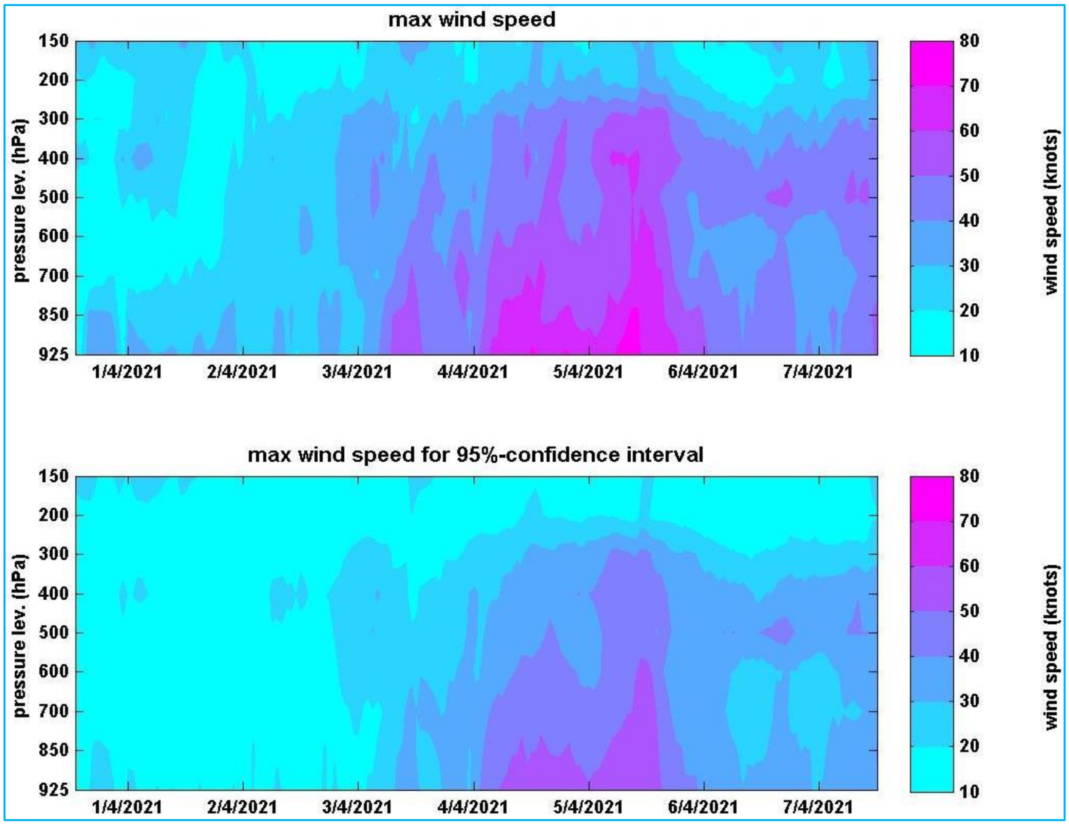

Fig. 8. Multi-level (925 to 150 hPa) maximum wind speed (upper) and maximum wind speed with 95% confidence interval (bottom)

about 70 to 80 knots, even though from the 95% confidence we see the maximum speed in the lower to near-upper level or 925 to 300 hPa with the maximum wind speed only reach 50 knots between 925 to 600 hPa. The maximum value exhibited in Fig. 8 (upper) could be an outlier, therefore shown in all intervals but not shown in a 95% confidence interval. However, without the direction, Fig. 8 could not represent the environment wind shear, thus, solely representing the wind speed for all atmospheric vertical columns. Furthermore, regarding tropical cyclone definition either from BMKG Indonesia or from BoM Australia, the system could be categorized into tropical cyclone if at least 34 knots of wind speed on the surface extending more than halfway around near the centre and persisting for at least six hours. Therefore, we need to take it more carefully when analyzing the tropical cyclone structure through wind conditions.

4. Conclusions

Some evidence is revealed through this research in terms of the characteristic and structure of tropical cyclone Seroja, especially since the genesis stage, turned into a tropical cyclone category, decayed and reintensified again far away from the origin position when the first time identified as a tropical disturbance. The vertical velocity was evaluated, not only in a horizontal but also in a vertical field, to investigate horizontal and tropical system vertical structure and development. The negative vertical velocity, especially in the middle level, which could indicate a strong updraft and system development shows a varied condition during the first intensification of the tropical cyclone, it then weakens for a while until it leaves the tropical cyclone category, then re-intensifies again at the end of April 7th, just before it finally returned into the tropical cyclone category. The disturbance system during genesis and first intensification stuck over the Sawu Sea to the southern Sawu Sea, which then moved southwest away from Timor quite faster. The broader negative-positive vertical velocity during the first intensification became narrow as the TC Seroja intensity became stronger but weakened as the negative vertical velocity elongated on April 7. The tightening of negative vertical velocity to the system centre proves to be a more organized tropical cyclone during the mature stage which also confirms the previous research by Smith (2021). Another evidence of a similar theory is the widespread convection during the weak intensity of tropical cyclones,

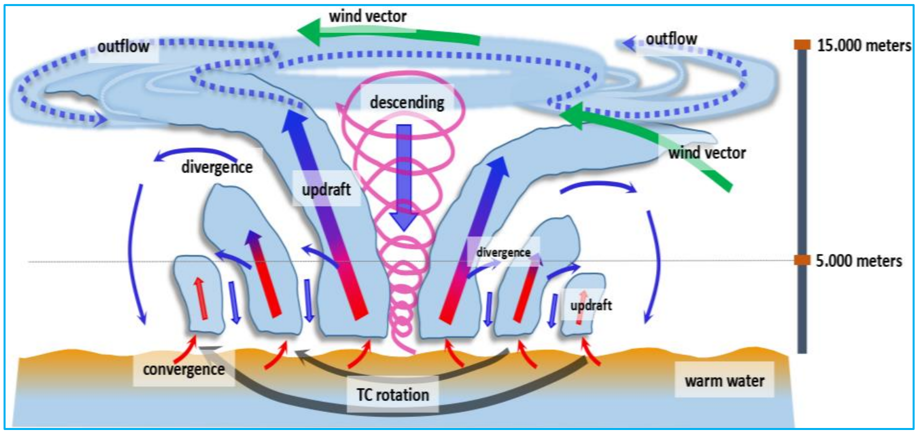

Fig. 9. A conceptual model for the vertical structure of TC Seroja during 1st intensification

while the more axisymmetric structure occurs if the TC intensity becomes greater as also mentioned by Sitkowski and Barnes (2009).

From either the vertical or horizontal structure of TC Seroja from April 4th until April 6th before the temporary (weakening) occurred, the strongest updraft in the middle level of the atmosphere accompanied by convergence in the lower to the mid-level indicates an unstable disturbance column due to latent heat released in the middle of the atmosphere (Frank and Ritchie, 1999) with sufficient heat transport from lower to upper eventually drives the TC development until the following two days. The system development remains present, even though pretty slow due to a strong wind shear which causes the convection to shift away, probably tilted relative to elevation from the system centre in the surface. The conceptual model is then exhibited in Fig. 9 to illustrate the vertical structure of TC Seroja during the first intensification and identified into the tropical cyclone category.

Fig. 9 depicts the vertical growth of the TC at the first intensification showing broad convection bands, especially in the west quadrant, with sufficient updraft inside the disturbance and downdraft over the clear region, indicating an adequate latent heat released to balance the energy transport to keep the environment unstable. A robust environment vertical wind tilted the vertical growth of the system away from that cyclone centre following the height, thus spreading the horizontal convection and shallowing the convection in the east quadrant. Divergence at the top level creates the outflow in all sectors, even though the strong wind shear leads the disturbance westward. The convergence that stopped at the level of 500 hPa, sharply changed with the divergence at the first intensification is presumably the result of robust environment wind at level 500 to 400 hPa. Since we limited the investigation solely to the first development and intensification stage, the structure and development characteristics during the first intensification of TC Seroja, which is typically a tropical cyclone over the tropics revealed. Further study of tropical cyclones in the tropics through examining other parameters and evidence needs to be explored.

Authors' Contributions

Ida Pramuwardani: Lead the manuscript writing, decide the methodology, summarise the findings and write the manuscript.
Fakhrul Alam: collected and analysed the data, wrote the manuscript.
Andri Ramdhani: collected and analysed the data, wrote the manuscript.
Guswanto: collected and analysed the data, wrote the manuscript.

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