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The Influence Of Atmosphere On Tropical Cyclone Freddy In The Lesser Sunda Islands

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ABSTRAK

Indonesia sering mengalami fenomena atmosfer berupa Siklon Tropis setiap tahunnya, karena letak geografisnya yang berada di daerah tropis. Terjadinya Siklon Tropis di Indonesia berlangsung sekitar 3 jam hingga 18 hari ketika bulan Februari hingga April. Salah satu Siklon Tropis yang berlangsung di Indonesia pada tahun 2023, yaitu Siklon Tropis Freddy. Penelitian ini bertujuan untuk menjelaskan karkateristik Siklon Tropis Freddy, kondisi atmosfer, serta pengaruhnya terhadap curah hujan di Sunda Kecil. Data yang digunakan berupa data citra satelit Himawari-9 band IR (13), NWP, parameter meteorologi ERA-5, dan GSMaP dengan interval waktu setiap 6 jam sekali dari selama 5-7 Februari 2023. Siklon Tropis Freddy yang terbentuk di selatan Nusa Tenggara Timur terbentuk pada 5 Februari 2023 dan terus berkembang menjadi bentuk sempurna pada 6 Februari 2023 pukul 12.00 UTC yang erus berkembang dan bergerak ke arah barat. Faktor pembentukan siklon tropis ini berasal dari tingginya *Sea Surface Temperature* (SST), adanya *Intertropical Convergence Zone (*ITCZ), serta aktifnya *Madden Julian Oscillation* (MJO) yang berada di fase 4. Jarak terdekat antara lokasi terjadinya Siklon Tropis Freddy dengan daratan berlangsung pada 6 Februari 2023 pukul 18.00, yaitu 187 km terhadap Pulau Sumba. Di sisi lain, dampak Siklon Tropis terhadap parameter meteorologi berupa terjadinya updraft di wilayah Kepulauan Sunda Kecil dan peningkatan transpor kelembaban di sisi utara dan selatan. Selain itu, siklon tropis ini berdampak secara *remote effect* terhadap kejadian hujan di Kepulauan Sunda Kecil.

Kata Kunci: Atmosfer, Siklon Tropis Freddy, Himawari-9, Curah Hujan, Kepulauan Sunda Kecil

ABSTRACT

Indonesia frequently experiences atmospheric phenomena form Tropical Cyclone annually due to its geographical location situated in tropical regions. The occurrence of Tropical Cyclones in Indonesia typically lasts from 3 hours to 18 days during February to April. One of the Tropical Cyclones that occurred in Indonesia in 2023 was Tropical Cyclone Freddy. This research aims to elucidate the characteristics of Tropical Cyclone Freddy, atmospheric conditions, and its influence on rainfall in the Lesser Sunda Islands. The data utilized include Himawari-9 satellite imagery in the IR (13) band, NWP, ERA-5 meteorological parameters, and GSMaP with time intervals every 6 hours from 5-7 February 2023. Tropical Cyclone Freddy, formed south of East Nusa Tenggara on February 5, 2023, and continued to develop into a mature form on February 6, 2023, at 12:00 UTC, progressing westward. The factors contributing to the formation of this tropical cyclone include elevated Sea Surface Temperature (SST), the presence of the Intertropical Convergence Zone (ITCZ), and the active phase 4 of the Madden Julian Oscillation (MJO). The closest distance between the location of Tropical Cyclone Freddy's occurrence and the mainland occurred on February 6, 2023, at 18:00, at 187 km off Sumba Island. On the other *hand, the impacts of the tropical cyclone on meteorological parameters include the occurrence of updrafts in the Lesser Sunda Islands region and an increase in moisture transport to the north and south. Additionally, Tropical Cyclone Freddy exerts a remote effect on rainfall events in the Lesser Sunda Islands.*

Keywords: *Atmosphere, Tropical Cylone Freddy, Himawari-9, Rainfall, Lesser Sunda Islands*

INTRODUCTION

Tropical cyclone is a significant natural weather phenomenon in tropical regions characterized by the formation of a low-pressure center (Emanuel, 1988) and Sea Surface Temperature (SST) must be at least 26.5°C (Tory & Dare, 2015). This occurs due to the ocean circulation interacting with the atmosphere at the sea surface (Asrianti et al., 2013). Both of these interactions often occur in tropical regions because tropical areas receive solar radiation, resulting in higher sea surface temperatures compared to subtropical or polar regions (Ismail et al., 2017). In general, tropical cyclones have a lifespan of approximately 3 hours to 18 days (Kurniawan et al., 2021) that is active during the months of February to April (Badan Metorologi Klimatologi dan Geofisika, 2023).

Tropical cyclones that occur in Indonesia have been frequent, and research addressing them, such as Tropical Cyclone Seroja in East Nusa Tenggara, focuses on the maritime conditions (Avrionesti et al., 2021), cause (Latos et al., 2023), and rainfall conditions (Kurniawan et al., 2021). Furthermore, there is research discussing the impact of Tropical Cyclone Claudia on wave heights in the regions of Nusa Tenggara, Java, and Bali (Islamiyah et al., 2021).

Tropical cyclones have a direct impact on the increase in precipitation (Agustín Breña-Naranjo et al., 2015; Maass et al., 2018; Yin et al., 2010), extreme waves (Fang et al., 2017), and wind speed (Sparks, 2003). On the other hand, there is an indirect influence in the form of flooding (Zhang et al., 2017), landslide (Zinke, 2021) and changes in ecosystems and coastal erosion (Meixler, 2017).

Therefore, this study aims to elucidate the characteristics of Tropical Cyclone Freddy, atmospheric conditions, and its impact on rainfall in the Lesser Sunda Islands that occurred in the year.

RESEARCH METHODS

The studied research location is situated in the Lesser Sunda Islands region, encompassing the provinces of Bali, West Nusa Tenggara, and East Nusa Tenggara, with coordinates ranging from 5°LS to 20°LS and 113°E to 128°E during the research period from February 5 to 7, 2023 (Figure 1).

The data processing was conducted using SATAID, Climate Data Operator (CDO), and GraDS, utilizing satellite imagery from the Himawari-9 satellite operated by the Japan Meteorological Agency (JMA). This satellite features a temporal resolution of 10 minutes. (Wan & Gao, 2024), while its spatial resolution is in the range of 0.5 to 2 km (Bessho et al., 2016) utilizing the IR band, specifically band 13, is employed for visually identifying Tropical Cyclone Freddy through observation. Additionally, the Black Body Temperature values (T_{BB}) can determine the Convective Index (CI) (Adler & Negri, 1988; Mapes & Houze, 1995; Nitta & Sekine, 1994; Sakurai et al., 2005) to observe convective clouds (Samrin et al., 2019) with a threshold value of 253 K (Adler & Negri, 1988).

The stability indices utilized include the K-Index (KI), Lifted Index (LI), Total-totals Index (TT), Showalter Stability Index (SSI), Severe Weather Threat (SWEAT), and Convective Available

Potential Energy (CAPE) (Table 1). The K-Index is designed to assess the potential for convective activity based on atmospheric humidity and vertical temperature (Hutagalung et al., 2022), LI (Lifted Index) for potential atmospheric stability conditions (Azani & Kusumawardani, 2022), SSI (Stability Severity Index) is used to measure atmospheric stability by calculating the lifting force on an air parcel in the layer between 850-500 mb (Diniyati et al., 2021), TT, SWEAT, and CAPE for indications of potential adverse weather (Azani & Kusumawardani, 2022; Prasetyo et al., 2020; Wirjohamidjojo et al., 2014) and monitor the level of convectivity that occurs (Yunita & Zakir, 2016).

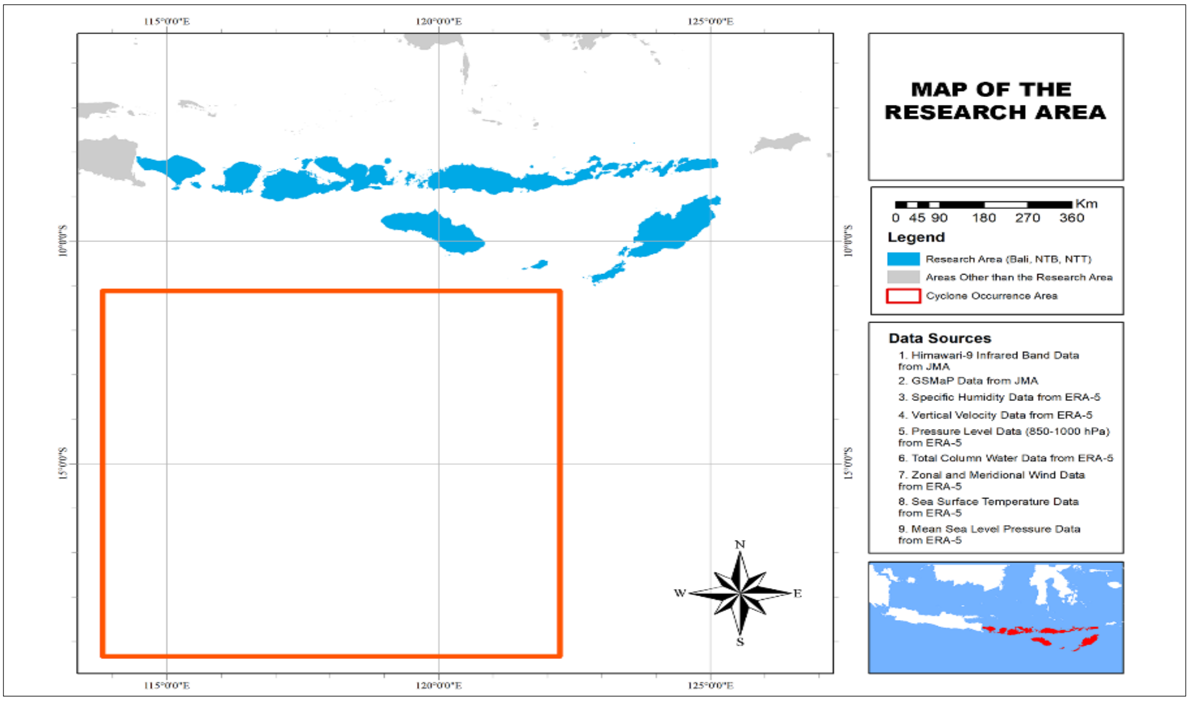

Figure 1. Research Location

Table 1. The Criteria Of Stability Indices

Index	Weak	Moderate	Strong
K Index	<29	29 to 37	>37
LI Index	>-2	-2 to -6	<-6
TT Index	<42	42 to 46	>46
SSI	>4	4 to -4	<-4
CAPE	<1000	1000 to 2500	>2500
Index	Weak	Moderate	Strong

Sources: (Fibriantika & Mayangwulan, 2020; Prasetyo et al., 2020; Wirjohamidjojo et al., 2014)

The meteorological data used to observe the atmospheric conditions during Tropical Cyclone Freddy include specific humidity, Sea Surface Temperature, zonal wind, Mean Sea Level Pressure, meridional wind, vertical velocity, and total column water with air pressure ranging from 850 to 1000 hPa, sourced from ERA-5. ERA-5 data can provide a more accurate estimation of atmospheric conditions due to the extensive utilization of historical data in its forecastin (Meng et al., 2018) and improved spatial resolution on a global scale (Hersbach et al., 2020) Thus, it is widely utilized and has proven its superiority. Specific humidity data will be subsequently employed for the visualization of divergence and Low-Level Moisture Transport (LLMT) using their respective equations. (Lélé et al., 2015).

$$\bar{Q} = \frac{1}{g}\int_{850}^{1000} q\bar{V}dp \qquad (1)$$

Description:

$\bar{Q}$ = Humidity Transport ($kgm^{-1}s^{-1}$)

g = Gravitational Acceleration (ms^{-1})

q = Specific Humidity (gr/kg)

$\bar{V}$ = Horizontal Wind Vector

Furthermore, rainfall distribution estimates utilize GSMaP (Global Satellite Mapping of Precipitation) satellite image data, which has proven its reliability in Indonesia due to its spatial resolution of 0.1°x0.1° (Ramadhan et al., 2023). The GSMaP rainfall data in Bali shows a strong positive correlation value of 0.889 with respective values of MBE and RMSE, namely 0.061 and 0.595 (Duwanda & Sukarasa, 2021). The impact of Tropical Cyclone Freddy on rainfall distribution in the Lesser Sunda Islands can be observed through the visualization of rainfall estimation.

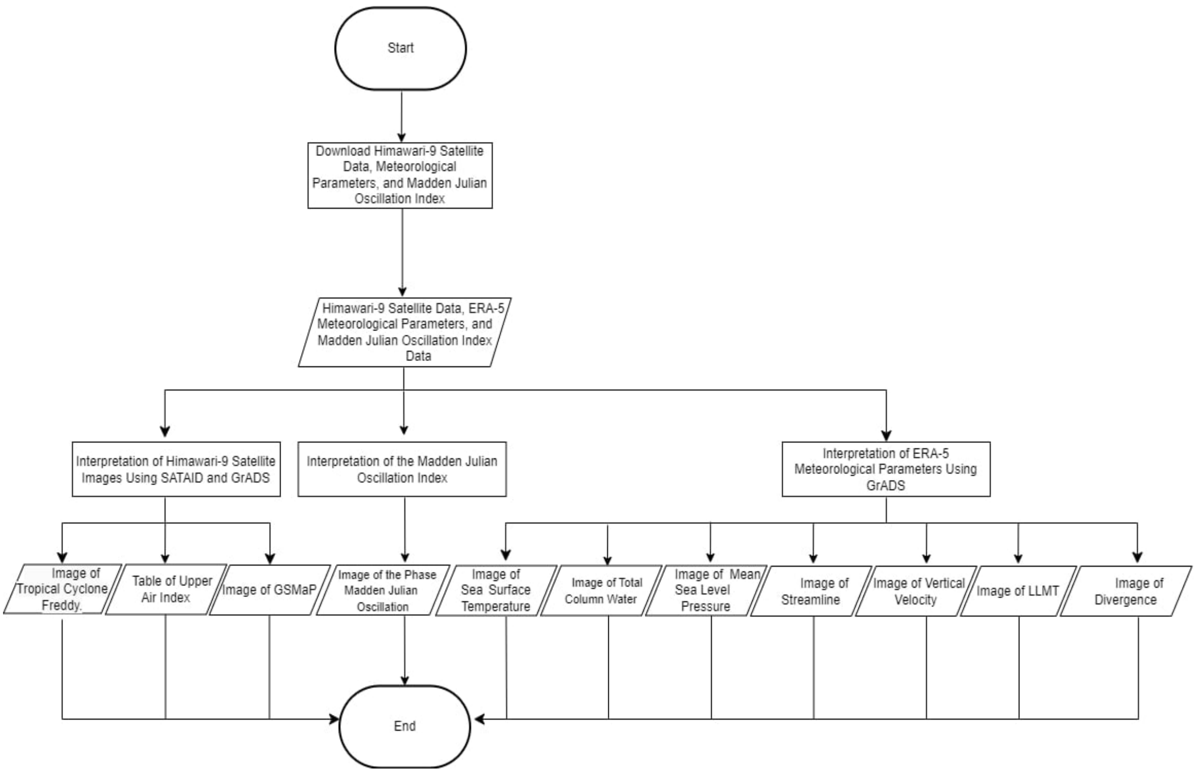

Figure 2. Flowchart

RESULT AND DISCUSSION

The Development Of Tropical Cyclone Freddy

Figure 3 illustrates the process and development of Tropical Cyclone Freddy, located south of Sunda Strait on February 5-7, 2023 with time intervals of every 6 hours. From February 5, 2023 to February 6, 2023 at 00:00 UTC, the tropical cyclone was still undergoing formation, then began to exhibit a vortex shape at 06:00 UTC continuing to develop and move westward. The closest distance between Tropical Cyclone Freddy and the land on February 6, 2023 at 06:00 UTC, was 257 km from Sumba Island. By 12:00 UTC, Tropical

Cyclone Freddy had formed completely with its closest proximity to land being 215 km from Sumba Island. Subsequently, the tropical cyclone moved westward starting to move away from Sumba Island with the closest distance to the Lesser Sunda region, specifically the southern part of West Nusa Tenggara, being 187 km on February 6, 2023 at 18:00 UTC. Bali experienced its closest proximity to Tropical Cyclone Freddy on February 7, 2023 at 06:00 UTC at a distance of 313 km and continued to move away from the Lesser Sunda region.

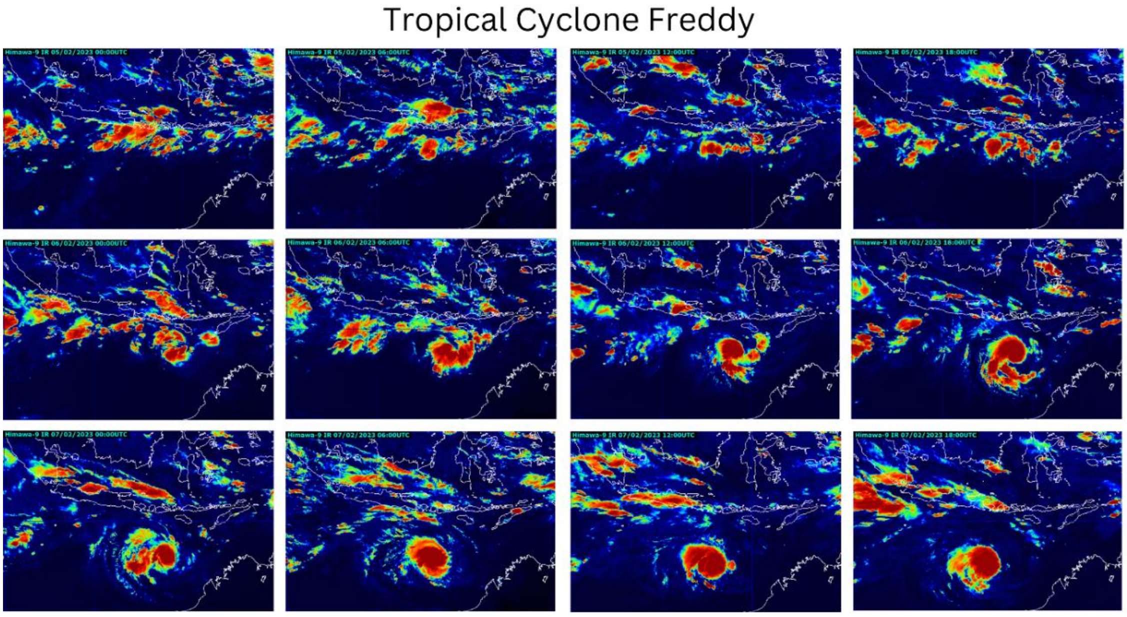

Figure 3. Tropical Cyclone Freddy

Table 2. Upper Air Index

Date	Time (UTC)	TBB (Kelvin)	KI (Celcius)	LI (Celcius)	TT (Celcius)	SSI (Celcius)	CAPE (J/kg)	SWEAT
5	00	204.9	35.6	-2.4	42.1	0.7	353	256
	06	197.1	34.4	-2.6	40.7	1.7	548	165
	12	199.3	34.6	-2.3	41.0	1.3	411	153
	18	193.1	34.8	-2.3	40.9	1.5	401	172
6	00	191.3	36.7	-2.3	41.7	0.3	609	238
	06	189.0	33.7	-2.7	40.6	1.5	601	235
	12	186.5	36.4	-2.1	41.2	0.8	320	238
	18	187.9	35.8	-2.5	41.7	0.7	441	309
7	00	185.7	37.3	-3.4	42.4	-0.2	1256	249
	06	186.7	36.8	-3.2	41.6	0.4	880	183
	12	187.6	37.0	-3.3	41.7	0.4	901	207
	18	180.4	37.6	-1.2	42.1	-0.1	99	423

Table 2 illustrates the upper air conditions every 6 hours on February 5-7, 2023 during the occurrence of Tropical Cyclone Herman. Atmospheric instability conditions can be observed based on the atmospheric instability index values using the NWP method (Asmita & Saragih, 2022) Thus, it can provide information regarding the occurrence of heavy rainfall. The KI Index and SWEAT values indicate moderate and strong categories with a minimum value of 33.7°C, while the maximum is 37.6°C, indicating convective activity for the KI Index. Furthermore, LI and SSI fall into the moderate category, with TT Index and CAPE categorized as weak and moderate.

Sea Surface Temperature

Figure 4 depicts the Sea Surface Temperature (SST) conditions every 6 hours. It can be observed that the temperature formed south of the Lesser Sunda Islands ranges from 29°C to 29.5°C, indicated by the light green color. This signifies that the Sea Surface Temperature contributes to the formation of Tropical Cyclone Freddy, as its temperature exceeds 26.5°C, considering that the formation of tropical cyclones requires high Sea Surface Temperature (SST) (Pillay & Fitchett, 2021).

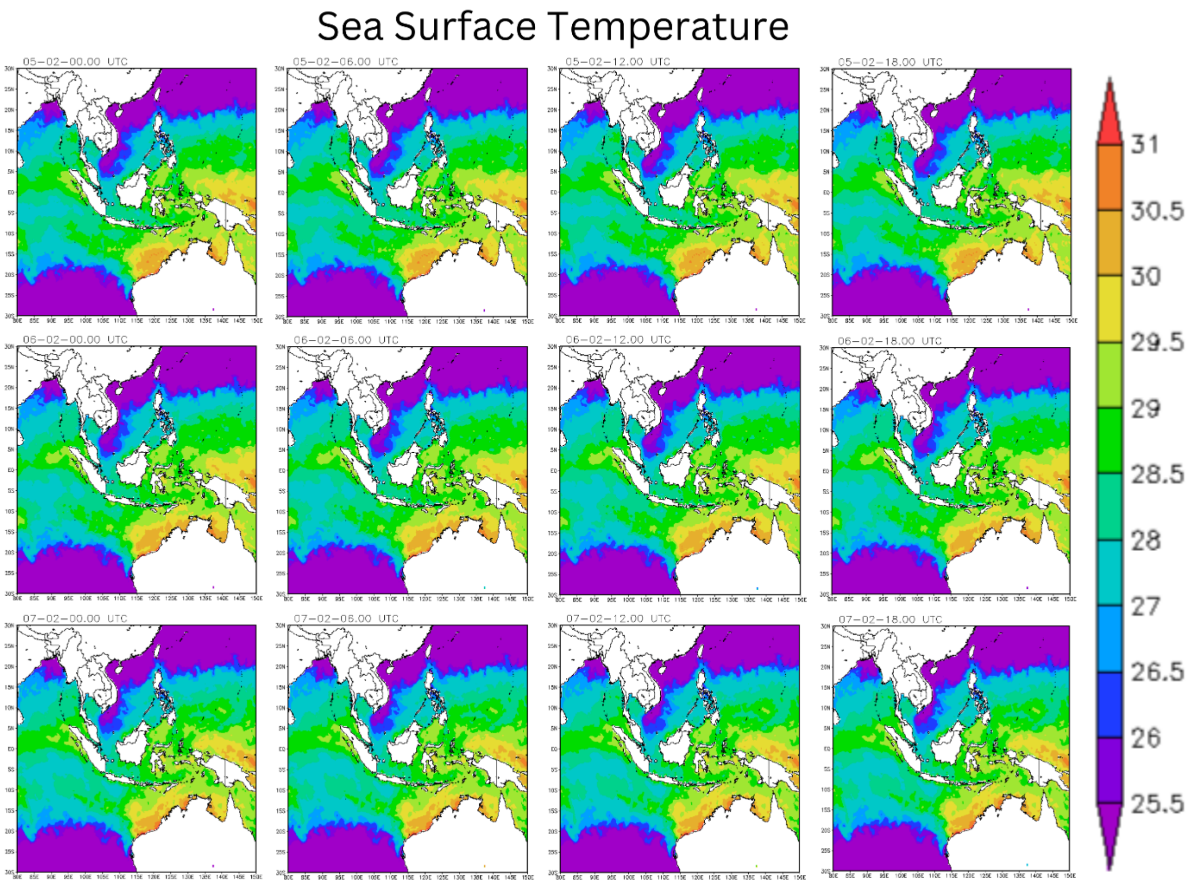

Figure 4. Sea Surface Temperature

Streamline

Observed in Figure 5 is the presence of the Intertropical Convergence Zone (ITCZ), indicating the convergence of wind directions from the Asian and Australian continents, coupled with the warm Sea Surface Temperature (SST) conditions. This leads to the formation of several wind vortices south of the Lesser Sunda Islands (Yan, 2005). Based on the aforementioned, the Intertropical Convergence Zone (ITCZ) plays a role in the formation of Tropical Cyclone Freddy.

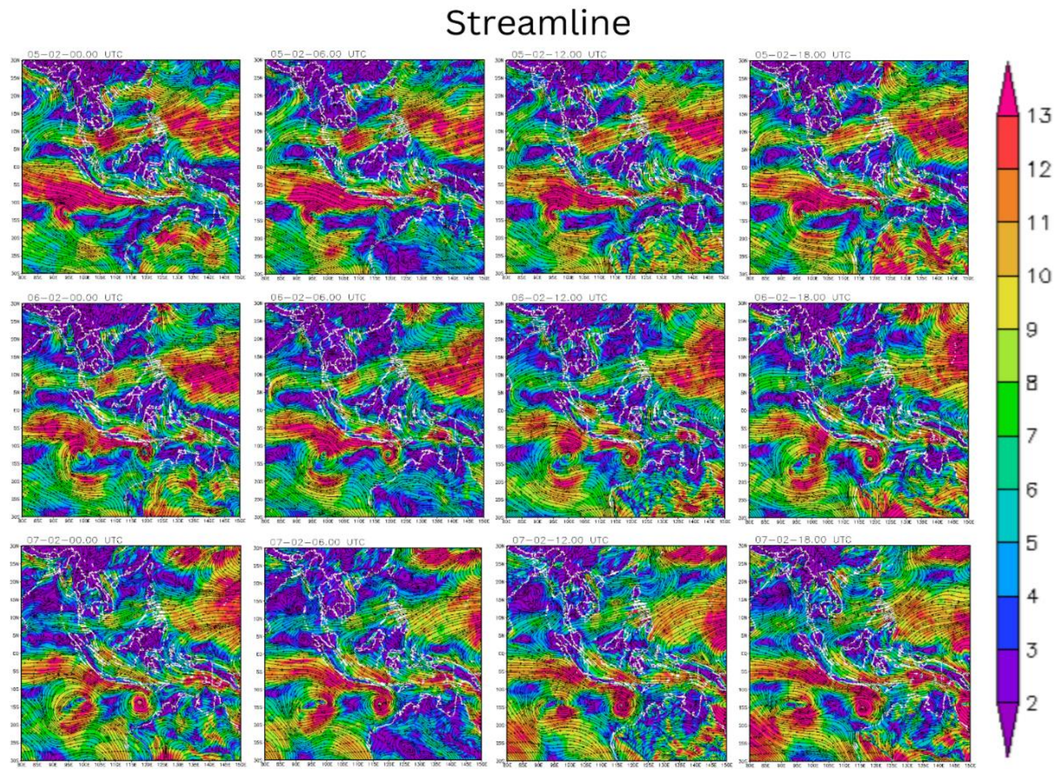

Figure 5. Streamline

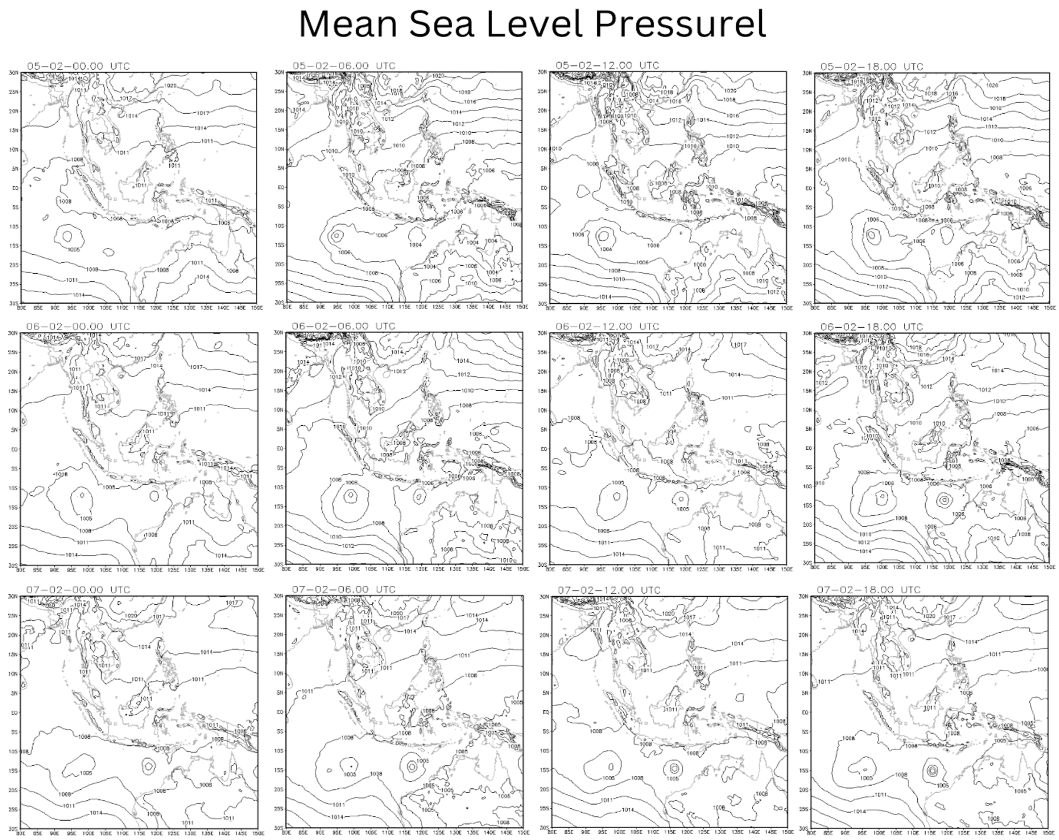

Figure 6. Mean Sea Level Pressure (hPa)

Mean Sea Level Pressure

Figure 6 illustrates the Mean Sea Level Pressure (MSLP) conditions used to analyze the factors leading to the formation of Tropical Cyclone Freddy. Spatial mapping of this parameter can indicate the presence of the Monsoon Trough (MT) and Monsoon Ridge (MR), serving as indicators of the influence on tropical cyclone formation (Zong & Wu, 2023). Based on the above diagram, the Monsoon Trough (MT) occurred on February 6, 2023, at 18:00 UTC, as well as on February 7, 2023, at 06:00, 12:00, and 18:00 UTC. Therefore, the Monsoon Trough (MT) is not a contributing factor to the formation of Tropical Cyclone Freddy in the Sunda Islands.

Madden Julian Oscillattion

Figure 7 illustrates the phases of the Madden-Julian Oscillation (MJO) during the occurrence of Tropical Cyclone Freddy on February 5-7, 2023. The phases, indicated by the green-colored line, represent the MJO events in February, with the tropical cyclone's timing situated in phase 4, and its amplitude exceeding one as it lies outside the circle (Purwaningsih et al., 2020). Therefore, the Madden-Julian Oscillation (MJO) influences the formation of Tropical Cyclone Freddy, considering that phase 4 indicates the significance of the MJO phenomenon in central Indonesia (Suhardi et al., 2018).

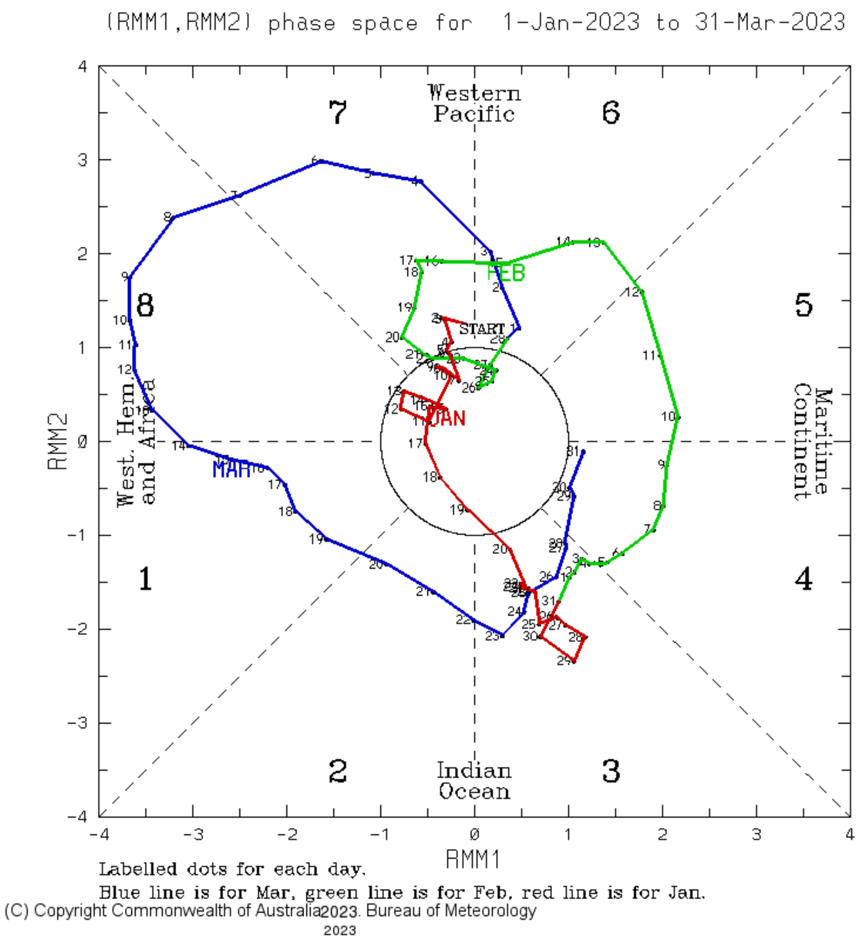

Figure 7. Phase of Madden Julian Oscillation (*http://www.bom.gov.au/climate/mjo/*)
.

Vertical Velocity

Figure 8 illustrates spatial vertical velocity, where decreasing values indicate the occurrence of updrafts lifting air masses to higher layers (Pujiastuti & Nurjaman, 2019) thus resulting in an increase in convective clouds (Dewi & Kristianto, 2018). Updraft was observed in the northern regions of Manggarai Regency, West Manggarai, and East Manggarai on February 5, 2023 from 06:00 UTC to 18:00 UTC. Subsequently, there was a fluctuation in the distribution of updraft, with Bali Province experiencing updraft only at 00:00 UTC on February 5, 2023. The recorded minimum value was -3.4389 Pa/s, while the maximum value reached 1.1780 Pa/s.

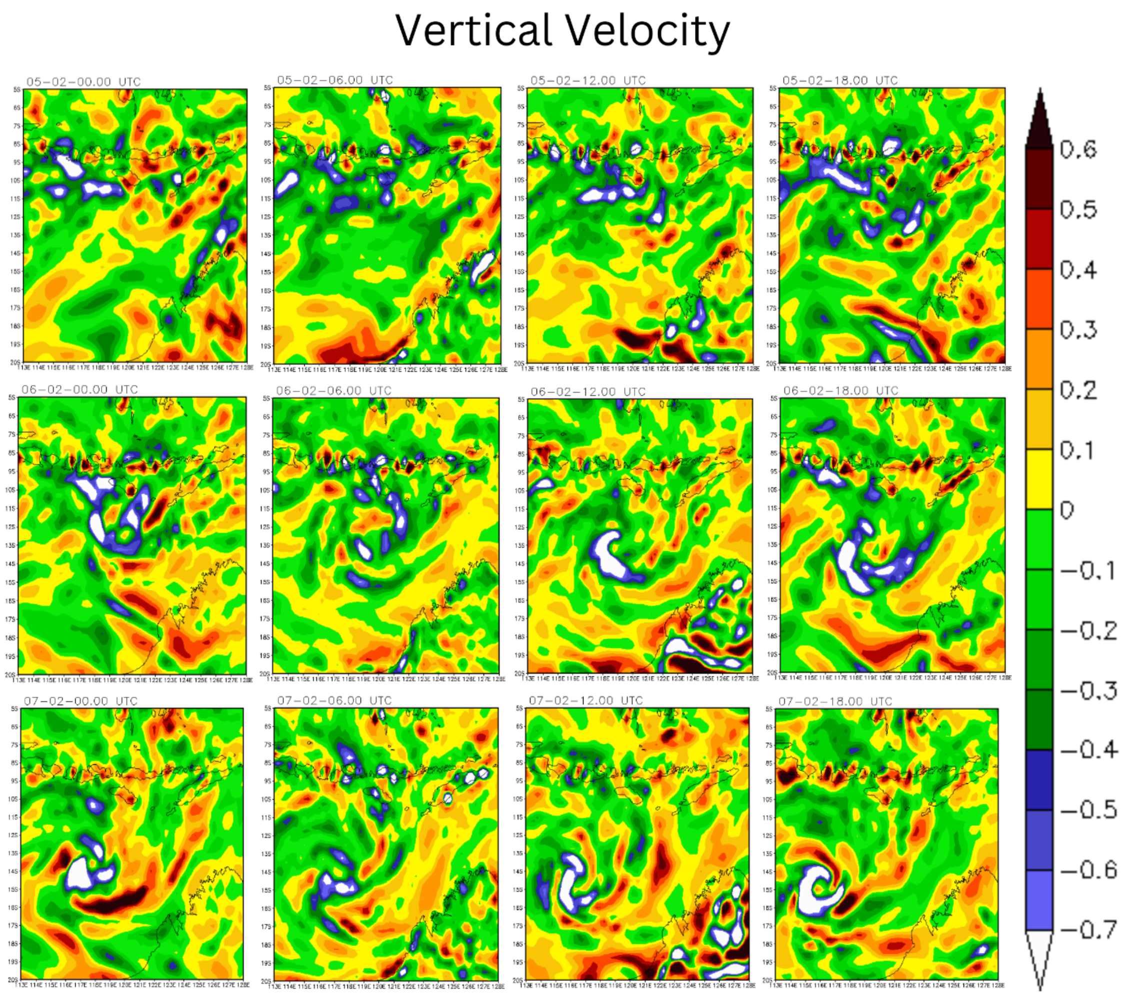

Figure 8. Vertical Velocity 850 hPa (Pa/s)

Low-Level Moisture Transport

In Figure 9, it illustrates moisture transport occurring in Indonesia. Higher humidity values indicate an increased potential for rainfall (Eryani et al., 2022) Thus, it becomes a dominant factor in the occurrence of rainfall. The image indicates that Tropical Cyclone Freddy influences moisture transport in the Lesser Sunda Islands, with red and dark blue colors representing higher humidity values compared to the surrounding areas depicted in white.

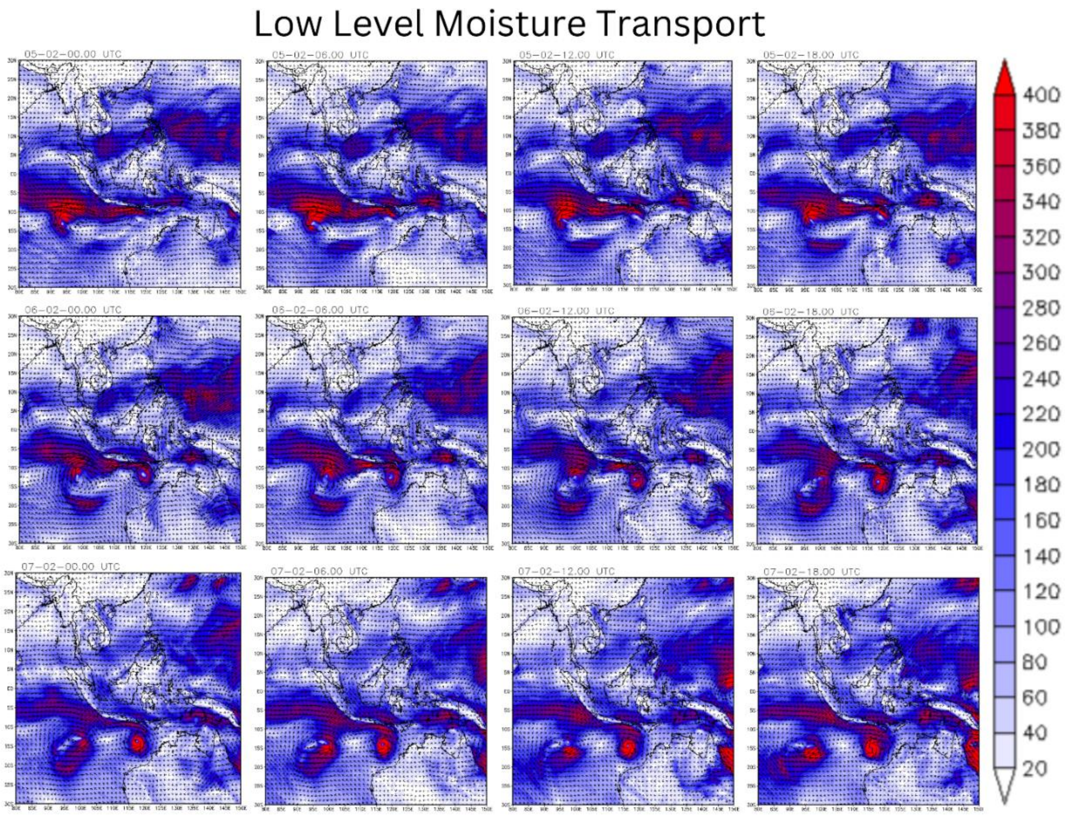

Figure 9. Low-Level Moisture Transport 850 hPa ($kgm^{-1}s^{-1}$)

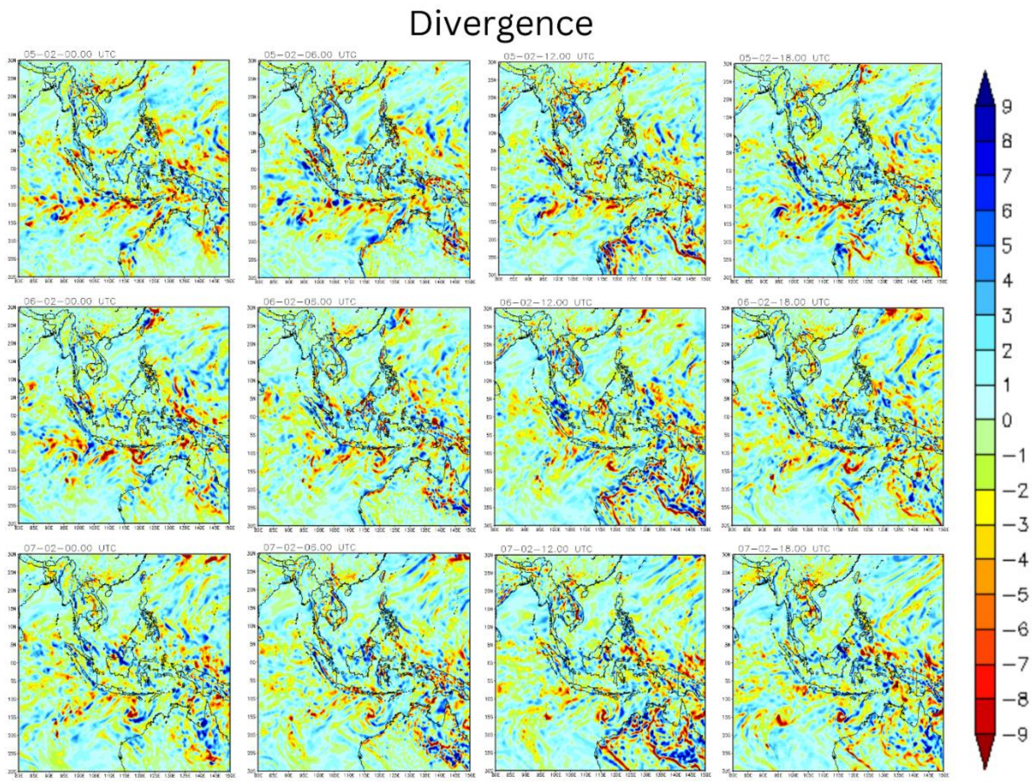

Figure 10. Divergence 850 hPa (s^{-1})

Divergence

In Figure 10, the state of convergence is indicated by negative values, while divergence is marked by positive values. The conditions of convergence and divergence change over time during the occurrence of Tropical Cyclone Freddy. Convergence leads to the updraft of air masses, thereby triggering the growth of convective clouds (Ayasha, 2022), Meanwhile, increasing divergence will reduce the likelihood of updraft formation in the cloud (Siregar et al., 2019).

Total Column Water

In Figure 11, the distribution of total column water in the form of water vapor, clouds, rain, and snow is depicted (Xu & Qiu, 2023). It can be seen that low total column water values occurred in a small part of East Manggarai Regency on February 5 2023 at 00.00 UTC. Subsequently, South Central Timor Regency and Kupang experienced consistently low total column water values throughout the study period. High total column water values do not necessarily indicate rainfall occurrences, as atmospheric instability conditions influence precipitation events. With sufficiently good atmospheric instability, the likelihood of precipitation occurrence increases (Dewi & Kristianto, 2018).

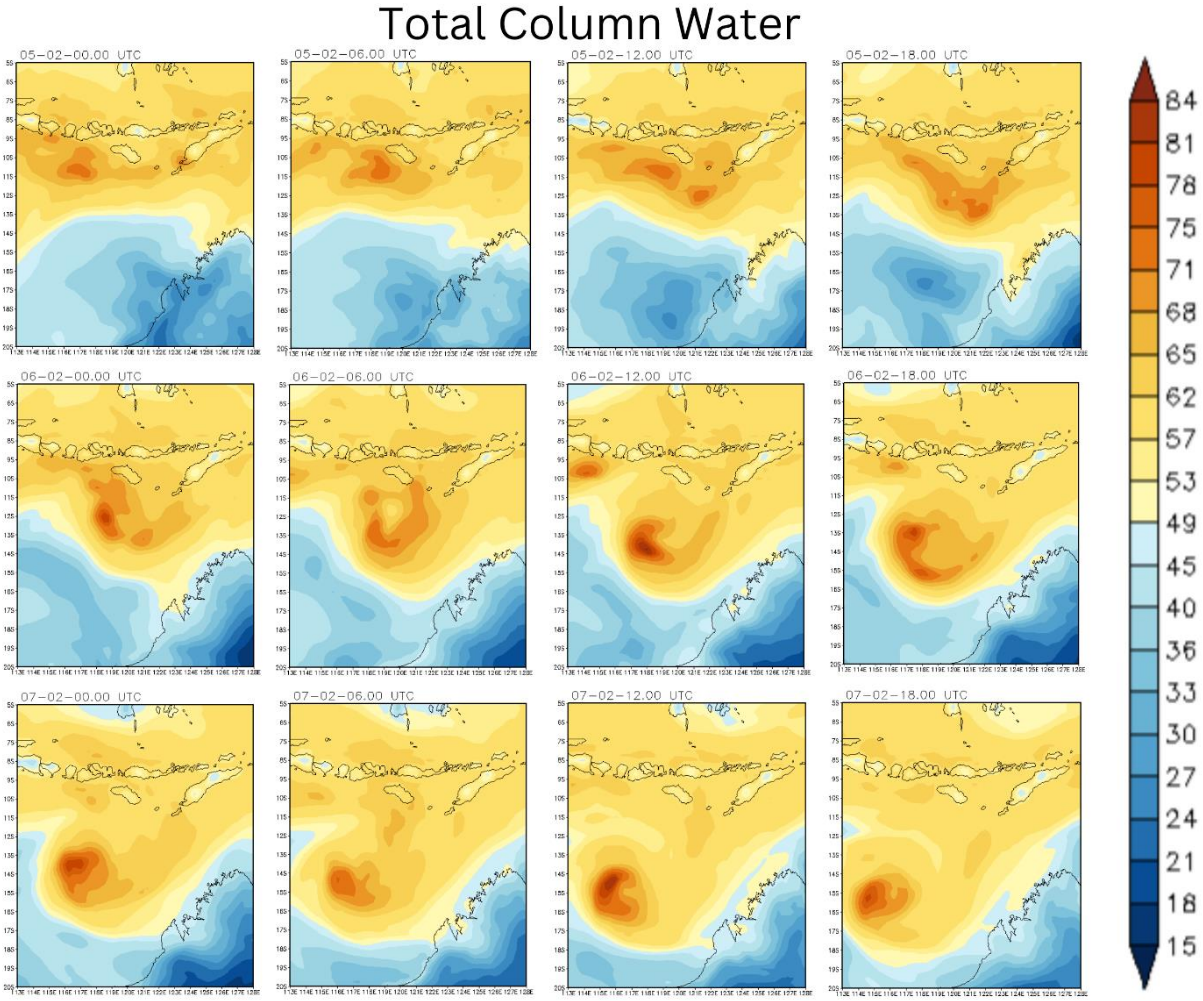

Figure 11. Total Column Water

GSMaP

Hourly rainfall can be categorized into several parts, namely light (1-5 mm/h), medium (5-10 mm/h), dense (10-20 mm/h), and very dense (>20 mm/h) (Gustari et al., 2012).

In Figure 12, the spatial pattern of rainfall distribution using GSMaP in the Lesser Sunda Islands during the occurrence of Tropical Cyclone Freddy is evident. It can be observed that the rainfall associated with the tropical cyclone exhibits intensities exceeding 25 mm/hour, indicating extremely heavy rainfall, marked by the purple color.

Rainfall was observed in Bali, Lombok Island, Sumba Island, and Timor Island on February 5, 2023 at 00:00 UTC when Tropical Cyclone Freddy had not yet formed. Tropical cyclone formation commenced on February 6, 2023 at 06:00 UTC, with the impact of rainfall distribution evident around Lembata Island. The westward movement of Tropical Cyclone Freddy affected the rainfall distribution, moving from east to west, with the province of Bali and its vicinity experiencing rainfall on February 7, 2023 at 18:00 UTC.

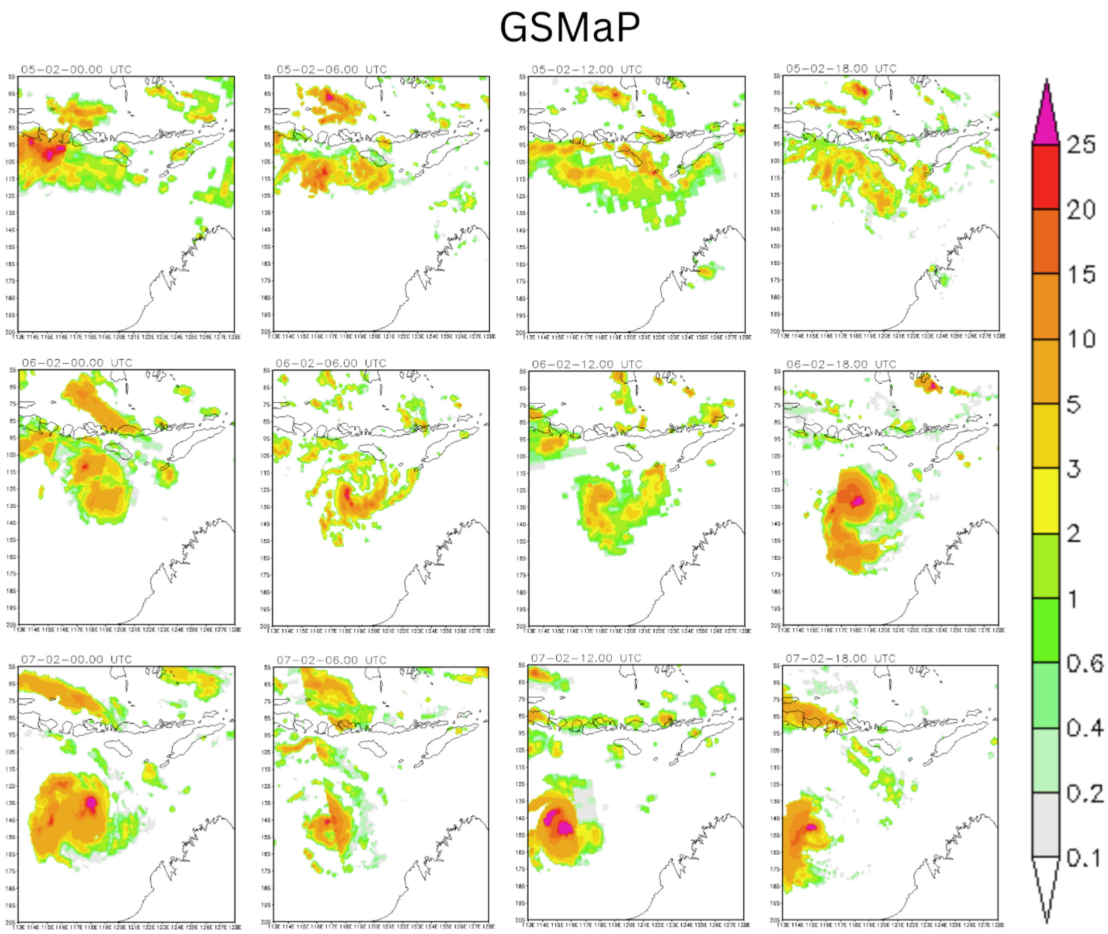

Figure 12. GSMaP Rainfall Distribution

CONCLUSIONS

Tropical Cyclone Freddy, formed south of the Lesser Sunda Islands, is indeed evidenced by atmospheric conditions and the presence of a convective cloud vortex. This tropical cyclone is not induced by the Monsoon Trough (MT) but rather influenced by factors such as high Sea Surface Temperature, the Intertropical Convergence Zone (ITCZ), and the Madden Julian Oscillation (MJO).

Updraft occurs in various regions due to the cyclonic motion of Tropical Cyclone Freddy, thereby increasing the potential for rainfall, accompanied by low T_{BB} values leading to the growth of convective clouds. On the other hand, moisture transport on the northern and southern sides of the Lesser Sunda Islands is induced by Tropical Cyclone Freddy, supplying water vapor and resulting in rainfall on Sumba Island.

The influence of Tropical Cyclone Freddy on rainfall occurs through a remote effect, as the rainfall events take place after the tropical cyclone or when it has already moved away from the Sunda Islands region. However, the impact of the Tropical Cyclone on meteorological parameters results in the direct occurrence of updraft, thereby increasing the potential for rainfall events.

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