# RESPONSE OF UPWELLING PARAMETER BEFORE, DURING, AND AFTER TROPICAL CYCLONE
# (Case Study: Tropical Cyclone Marcus)

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**ABSTRACT**

Tropical cyclones (TC) can cause damage when they are on the land surface, but on the other hand TC contribute to ocean productivity through upwelling or downwelling when they pass through the ocean. Information of the location and timing of upwelling and downwelling is important for fishing - activities estimation. High chlorophyll-a concentrations and low sea surface temperatures are proxies for upwelling events in the ocean. This study aims to investigate the effects of the TC Marcus on the chlorophyll-a distribution in the Timor Sea using a combination of remotely sensed data from Aqua MODIS chlorophyll-a and ocean-atmosphere reanalysis outputs. The results showed that wind speed, sea surface temperature, salinity, and ocean currents were increased during the TC Marcus event. Spatial analysis reveals that the concentration of chlorophyll-a is high in the waters of the Timor Sea, at coordinates around 12°–13° S and 125°–129° E. High chlorophyll-a concentrations occurred before and after TC Marcus event, according to temporal analysis. The distribution of chlorophyll-a concentrations decreased on March 17–24, 2018, during the occurrence of the TC Marcus in the Timor Sea.

**Keyword:** tropical cyclone, chlorophyll-a, wind speed, sea surface temperature, Timor Sea.

## 1. Introduction

Tropical cyclones (TC) are powerful storms with a mean radius of about 150 to 200 km [2]. TC form primarily over large oceans, which typically have warm sea surface temperatures exceeding 26.5 °C [3]. TC is defined as a non-frontal synoptic-scale low-pressure system that develops over warm waters with convective thunderstorm activity and maximum sustained winds of at least 34 knots covering more than half of the area surrounding its centre, which could lasting for at least six hours [2]. TC formed in 10°- 20° regions from the equator, whereas in lower latitude regions (0°-10°S/N) TC are rarely formed. The southeastern part of the Indian Ocean is one of the areas that have high tropical cyclone activity.

According to wind speed and trajectory data obtained from the Bureau of Meteorology (BoM) on March 16, 2018, a TC called Marcus occurred in the Indian Ocean off the northwest coast of Australia at coordinates 10° S and 132.1° E with a speed of 34.8 knots. The trajectory of Marcus TC crossed the Timor Sea, thus affecting the waters conditions in the Timor Sea and its vicinity [4]. TC Marcus formed on March 14, 2018, in the northeastern Timor Sea on a strengthening monsoon trough and move to southeast [5]. TC Marcus was categorized as a severe TC when it was reaching category-5 of strength in the Indian Ocean on March 21 [6]. Marcus TC has reached its peak intensity around March 21, when it attained category-5 status according to the Saffir-Simpson scale (central cyclone pressure ≤ 919 mb). The highest wind speed during this cyclone event reached 135 knots, and the lowest pressure reached 905 mb. The TC began to weaken as it moved away from the warm water source that fuelled its strength.TC Marcus did not make landfall immediately in populated areas, but moved westward through very warm waters, reaching category-4 strength on March 22. After moving westward into open waters, TC Marcus continued to rapidly intensify, reaching its peak intensity on March 21 [7]. Severe TC Marcus formed in early March 2018 and reached its most intense strength around March 21 [5]. Starting on March 22, the influence of this air pressure began to diminish due to the presence of a high-level mid-latitude trough in the Indian Ocean, causing TC Marcus to turn south westward. From March 23-25, TC Marcus moved south eastward before eventually weakening and dissipating [6].

Wind are one of the main parameters influencing the characteristics of waters [8]. Generally, winds blowing over the sea surface affect other oceanographic parameters directly, such as upwelling [9]. Upwelling is an upward movement of seawater from a deeper layer to the surface layer [10]. This upward movement brings water with cooler temperatures, higher salinity, and rich nutrients to the surface, including chlorophyll-a (CHL). CHL is abundant in phytoplankton, which are producers in marine ecosystems [11]. Information regarding the spatial variability of CHL at the sea surface is essential, as it can be used to facilitate the management and utilization of fisheries resources [11]-[13]. Therefore, studies on the relationship between TC and (CHL) variability and upwelling parameters need to be conducted to obtain information on oceanographic conditions in areas affected by TC.

This study was conducted to analyse the response of physical oceanography parameters such as sea surface temperature (SST), surface wind, sea surface height (SSH), salinity, CHL variability in the waters of the Timor Sea and its vicinity before, during, and after the occurrence of TC Marcus. The focus of this research is on upwelling parameters alterations in 7 days before, during, and 7 days after TC Marcus event. This research is expected to provide information regarding the variability of upwelling parameters before, during, and after TC Marcus event, thus serving as a reference during similar events in the same or other locations and providing information for fishermen as a reference to create fishing maps to enhance fishing productivity.

## 2. Methods

**Data.** SST and near-surface wind data were obtained from ECMWF (European Centre for Medium-Range Weather Forecasts) (https://doi.org/10.1002/qj.3803) with a temporal resolution of 6 hours and a spatial resolution of 0.125° × 0.125°. CHL data were acquired from MODIS (Moderate-Resolution Imaging Spectroradiometer) (http://dx.doi.org/10.5067/MODIS/MYD08_M3.006) level 3 imagery on the Aqua satellite with a spatial resolution of 4 km. Level terminology is used to denotes broad categories of MODIS products; level 3 denotes global-gridded science products. SST, CHL, and wind speed data used were 7 days before, during, and 7 days after TC Marcus event, along with monthly climatology for 10 years (2006-2015). Daily sea surface salinity and ocean current data were obtained from Marine Copernicus (https://doi.org/10.48670/moi-00021) with a temporal resolution of 6 hours and a spatial resolution of 0.125° × 0.125° for 7 days before, during, and 7 days after TC Marcus event were used to support the analysis of upwelling processes [14].

**Method.** Upwelling parameters of wind speed, Ekman pumping velocity (EPV), CHL concentration, and SST over a period of 10 years from 2006 to 2015. Formulation of mean wind speed, SST, and CHL over 10 years using the climatological mean formula [15], which is:

$$A(x,y) = \frac{1}{n}\sum_{i=0}^{n} ai(x,y,t) \qquad (1)$$

where $A(x,y)$ represents the spatial mean value at position (x, y), and $ai(x,y,t)$ denotes the annual mean from 2006 to 2015 over space $(x,y)$ and time (t), where n is the number of data points. In this discussion, n=10data points (2006-2015). Cyclone Marcus occurred in March; therefore, the annual mean used is the mean for March over 10 years for normal value of upwelling parameters. The calculation of the upwelling parameter means of before, during, and after the occurrence of TC Marcus also employs the same calculation method as the climatological formulation. The calculation of EPV ($W_p$) is performed using Equation 1 by utilizing the calculated wind stress curl [16]. This equation expresses EPV as the result of wind stress curl (τ) divided by seawater density (ρ), coriolis (f), and factor of Δ, which represents the vertical scale factor. Delta (Δ) is a representation of the depth of the Ekman layer [17]. The unit of EPV is m/s.

$$W_p = \frac{1}{\rho f}\Delta \times \tau = \frac{1}{\rho f}\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right) \qquad (2)$$

where $\tau_x$ dan $\tau_y$ represent the zonal and meridional wind stress ($Nm^{-2}$), while ρ is seawater density (kg $m^3$). The value of EPV can be used to depict upwelling phenomena [18]. Upwelling were indicated by positive values of EPV, whereas negative values indicate downwelling.

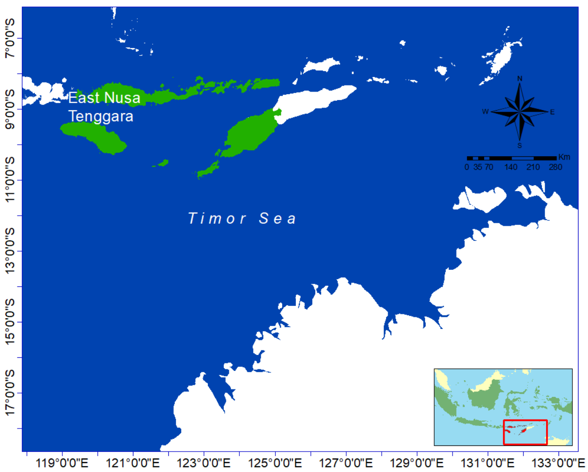


**Figure 1 Study area of Tropical Cyclone Marcus**

## 3. Results and Discussion

Based on TC Marcus's BoM report, a tropical depression was observed on March 14, 2018 moving south westward in alignment with the direction of the monsoonal flow in the sea between northern Australia and southern Timor Leste. This tropical depression intensified into TC Marcus on March 15 at 18.00 UTC (March 16, 03.30 Australian Central Standard Time), 2018, and reached category 2 after three days later. TC Marcus reached its peak intensity on March 21, 2018. By March 22, 2018, TC Marcus began to weaken so that it veering southward, and eventually dissipated on March 25, 2018.

**Table 1. Track of TC Marcus by Report of BoM [5]**

| Day | Hour (UTC) | Latitude (S) | Longitude (E) | Wind Speed 10 min (knot) | Pressure (hPa) | Note |
|---|---|---|---|---|---|---|
| 14 | 00 | -9 | 129 | 15 | 1005 | TD |
| 14 | 06 | -9 | 129 | 15 | 1005 | |
| 14 | 12 | -9 | 129.5 | 15 | 1005 | |
| 14 | 18 | -9 | 130 | 20 | 1005 | |
| 15 | 00 | -9.2 | 130.7 | 25 | 1005 | |
| 15 | 06 | -9.3 | 131.1 | 25 | 1000 | |
| 15 | 12 | -9.4 | 131.5 | 35 | 996 | |
| 15 | 18 | -9.8 | 132.1 | 35 | 996 | TC Marcus |
| 16 | 00 | -10.3 | 132.5 | 40 | 993 | |
| 16 | 06 | -10.9 | 132.2 | 45 | 988 | |
| 16 | 12 | -11.1 | 131.9 | 50 | 982 | |
| 16 | 18 | -11.5 | 131.7 | 55 | 982 | |
| 17 | 00 | -12.4 | 131 | 55 | 980 | |
| 17 | 06 | -13.1 | 130.1 | 50 | 988 | |
| 17 | 12 | -13.4 | 129.3 | 50 | 998 | |
| 17 | 18 | -13.8 | 128.7 | 60 | 983 | |
| 18 | 00 | -14.1 | 127.7 | 55 | 987 | |
| 18 | 06 | -14.6 | 126.4 | 40 | 992 | |
| 18 | 12 | -14.8 | 125.1 | 35 | 997 | |
| 18 | 18 | -14.9 | 124.1 | 40 | 994 | |
| 19 | 00 | -14.8 | 123.5 | 60 | 982 | |
| 19 | 06 | -15.4 | 122.8 | 75 | 969 | |
| 19 | 12 | -15.4 | 121.1 | 90 | 958 | Category 2 (Saffir-Simpson) |
| 19 | 18 | -15 | 119.7 | 90 | 961 | |
| 20 | 00 | -14.9 | 118.3 | 90 | 961 | |
| 20 | 06 | -14.6 | 116.9 | 90 | 959 | |
| 20 | 12 | -14.5 | 115.5 | 90 | 959 | |
| 20 | 18 | -14.5 | 113.6 | 100 | 951 | Category 3 |
| 21 | 00 | -14.3 | 112.2 | 110 | 935 | |
| 21 | 06 | -14.9 | 110.9 | 130 | 913 | Category 4 |
| 21 | 12 | -15 | 109.6 | 135 | 905 | Category 5 |
| 21 | 18 | -15.4 | 108.4 | 135 | 905 | |
| 22 | 00 | -15.8 | 107.4 | 130 | 907 | Category 4 |
| 22 | 06 | -16.6 | 106.7 | 110 | 931 | Category 3 |
| 22 | 12 | -17.4 | 106.4 | 100 | 942 | |
| 22 | 18 | -18.8 | 106 | 90 | 953 | Category 2 |
| 23 | 00 | -20 | 105.9 | 85 | 960 | |
| 23 | 06 | -21.3 | 105.9 | 80 | 964 | |
| 23 | 12 | -22.2 | 106.1 | 75 | 967 | Category 1 |
| 23 | 18 | -24 | 106.6 | 65 | 976 | |
| 24 | 00 | -25.7 | 107.1 | 60 | 977 | |
| 24 | 06 | -26.8 | 107.4 | 45 | 985 | End of TC Marcus |
| 24 | 12 | -27.6 | 107.5 | 30 | 998 | |
| 24 | 18 | -28.3 | 107.9 | 30 | 997 | |
| 25 | 00 | -28.8 | 108.4 | 25 | 998 | |

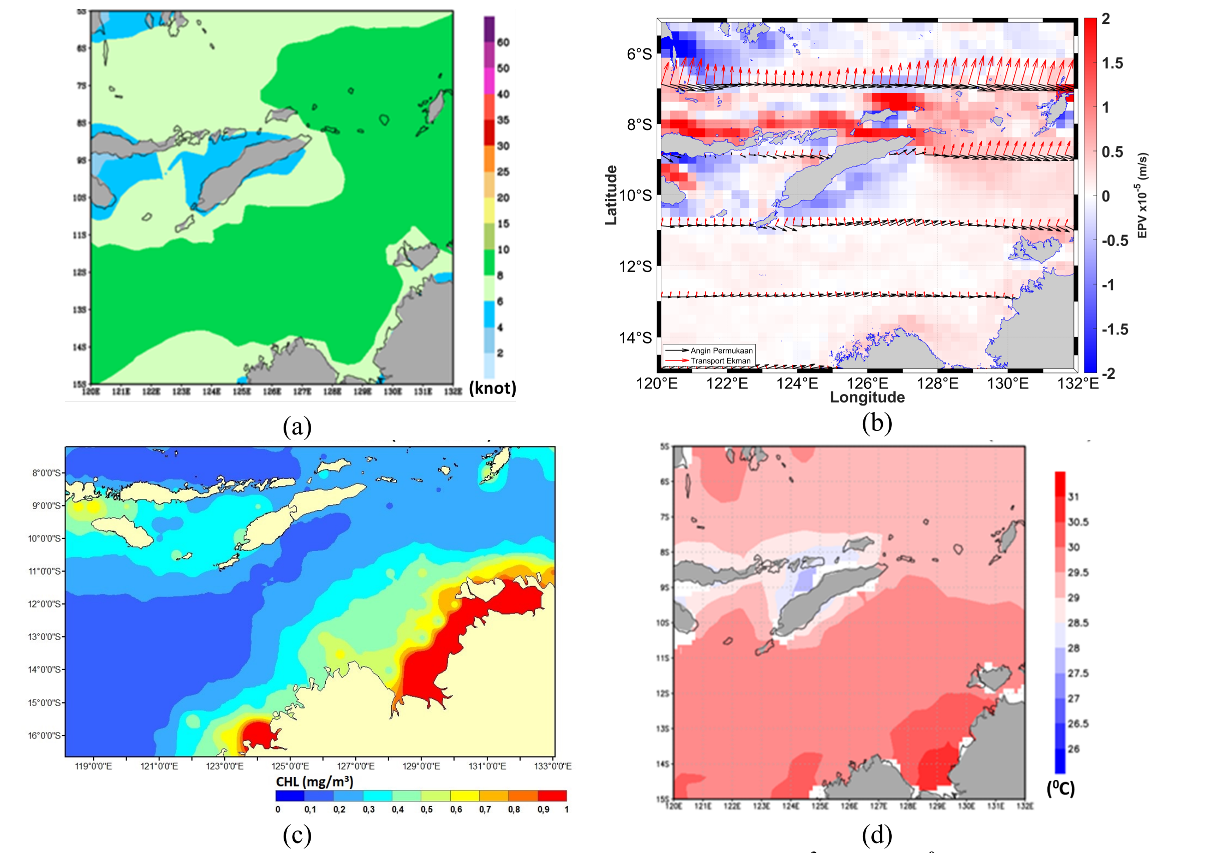


**Figure 2. Climatology of (a) Wind Speed (knot), (b) EPV (m/s), (c) CHL (mg/m$^3$), (d) SST ($^0$C) for the years 2006 - 2015**

**Climatology of Upwelling Parameters in March.** To understand the changes in the upwelling parameters, it is essential to establish baseline or average values of these parameters, as they serve as a baseline for assessing deviations and determining whether the observed changes are within the expected range of upwelling variability or show indicative of broader, potentially impactful shifts in upwelling dynamics. By comparing the current measurements against these baseline values, we can more accurately gauge the magnitude and significance of the observed changes. This comparison is crucial for distinguishing between natural upwelling variability and significant trends, allowing for a more profound interpretation of the data in the context of upwelling dynamics.

Figure 2 illustrates the average of wind speed, EPV, CHL concentration, and SST over a decade in the Timor Sea. The average of wind speed in the Timor Sea ranges between 8-10 knots. The EPV values over the past 10 years indicate that the area around the Timor Sea is mostly dominated by upwelling (red colour), except for the area near the coast of Nusa Tenggara Timur (NTT) which is dominated by downwelling (blue colour). The average of CHL intensity near the Timor Sea is approximately of 0.23 mg/m$^3$. Figure 2c shows a significant variety of the CHL distribution in the Timor Sea, ranging from 0.1 mg/m$^3$ to 1 mg/m$^3$. The average of SST temperature over past 10 years is approximately 29.5 to 30.5 °C in the Timor Sea.

**Upwelling Parameters Before, During, and After TC Marcus.** Figure 3 shows the condition of the Timor Sea before (9-15 March 2018), during (16-24 March 2018), and after (25-31 March 2018) TC Marcus. The average of wind speed before the TC is lower compared to during and after TC Marcus, ranging from 2 to 6 knot. Meanwhile, a twofold-increase of wind speed were detected during and after TC Marcus with ranges from 4 to 8 knot in the Timor Sea. The significant change of the wind speed were attributed to the low pressure condition at the core of TC Marcus which lead to the increase of average wind speed in the Timor Sea.

Figure 3b illustrates a rise in EPV values after the occurrence of TC Marcus exceeding its climatological averages, indicating the occurrence of upwelling. However, during and after TC Marcus, decline trend in EPV observed in the Timor Sea near the coast of NTT, indicating the occurrence of downwelling in that area. The overall CHL concentration in the waters of the Timor Sea ranges from 0.2 to 1.0 mg/m$^3$. The waters of the Timor Sea around the coast of Australia exhibit the highest concentrations of CHL, which varies in concentrations before, during, and after TC Marcus. Before TC Marcus occurred, CHL concentrations ranged from 0.6 to 1.0 mg/m$^3$, decreasing to 0.3 to 1.0 mg/m$^3$ during the cyclone, and then rising again to 0.5 to 1.0 mg/m$^3$after the TC Marcus.

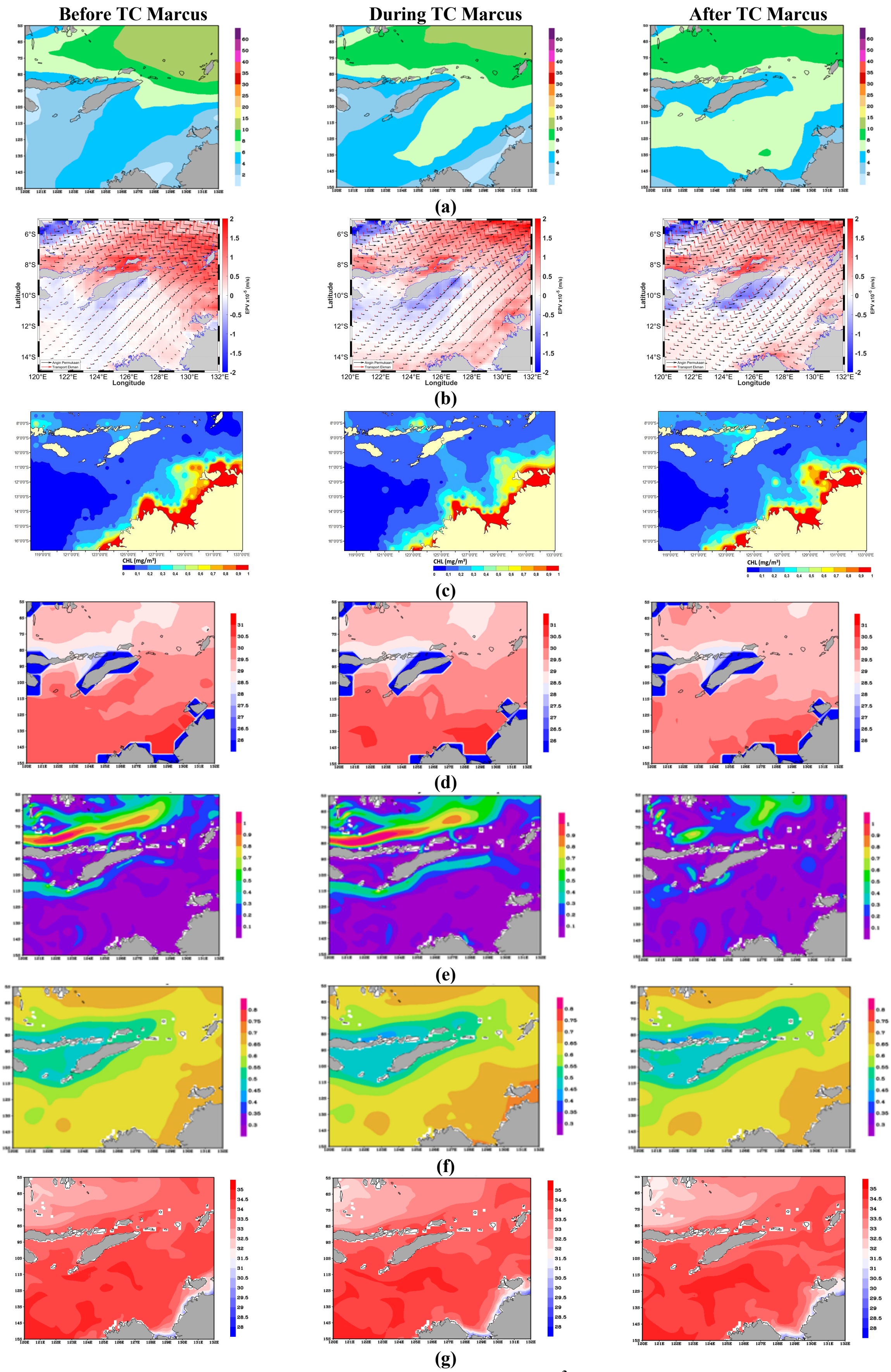


**Figure 3. Values of (a) Wind Speed (knot), (b) EPV (m/s), (c) CHL (mg/m$^3$), (d) SST (°C), (e) Ocean Currents (m/s), (f) SSH (m), and (g) Salinity (g/kg) before, during, and after TC Marcus**

Before the TC Marcus, SST ranged between 29 - 30 °C in the Timor Sea. Meanwhile during TC Marcus, SST increased to a maximum temperature of 31 °C in certain areas of the Timor Sea. Later, after the TC Marcus, SST decreased by 0.5 °C from before TC Marcus, marking the lowest temperature observed during the whole event (Figures 3). The SST value increasement can be attributed to the TC Marcus passing through the Timor Sea, which also resulted in decreased of CHL concentration. During TC Marcus, the cyclone led to increase in others parameter such as ocean current, SSH, and salinity due to the accumulation of water mass toward the center of TC Marcus and subsequent water mixing in the area[17].

Before the occurrence of TC Marcus, the upwelling mechanism was closely related to the atmospheric forcing induced by the developing storm system. This phenomenon likely led to the deepening of the ocean's mixed layer and enhance the nutrient availability [19]. The impact of these upwelling events includes alterations in biogeochemical parameters such as dissolved oxygen levels and phytoplankton distribution [20]. During the passage of TC Marcus, significant changes were observed in the upper ocean. The TC influenced SST and lead to a major impact on the intensity and trajectory of TC Marcus. Additionally, TC Marcus led to an increase in salinity by triggering plankton blooms. This phenomenon contributed to local primary productivity and may affected seasonal variations in CHL concentration [2]. The force of strong wind speed associated with TC Marcus likely enhance the upper ocean currents response [22]. These currents tend to tilt towards the right side of TC Marcus's trajectory in the Northern Hemisphere due to better wind current resonance [23].

**CHL Variability in Response to the Tropical Cyclone Marcus.** The pattern in Figure 4a demonstrates a positive correlation of 0.26 between sea surface wind (SSW) speed and CHL concentration, indicating that stronger winds lead to higher CHL concentration, vice versa. On the contrary, the temporal pattern Figure 4b shows a negative correlation of -0.067 between ocean currents and CHL concentration. This result indicates no significant relationship and show that both of current strength and CHL concentration didn't affect each other. However, we observe this overall correlation in the waters of the Timor Sea. As shown in Figure 3e, TC Marcus had marked effect on ocean currents speed in the Timor Sea waters near the NTT coastline. negative correlation of -0.38 between SST and CHL concentration was observed in the temporal pattern (Figures 4c) and indicated that SST influenced CHL concentration inversely; which mean that as SST rise, the CHL concentrations will decreases, vice versa. SST above 26.15 °C was recorded between March 17th -24th, meanwhile CHL concentrations was below 0.3 mg/m$^3$, dropping as low as 0.12 mg/m$^3$ on March 17th. Following TC Marcus, a noticeable decrease in SST and a sharp increase in CHL concentration was recorded on March 25th (highlighted in red-coloured box). Based on Figure 4d, there is a negative correlation of -0.17 between SSH and CHL concentration, implying that SSH is associated with CHL concentration. Higher (lower) SSH values can indicate upwelling (downwelling) occurrence [19], and correspondingly, higher SSH can lead to lower CHL concentration, vice versa [24]-[27]. The positive correlation of 0.36 between salinity and CHL concentration (Figure 4e) suggests that CHL concentrations were directly proportional to salinity level. As salinity increase, CL concentration also rise, vice versa.

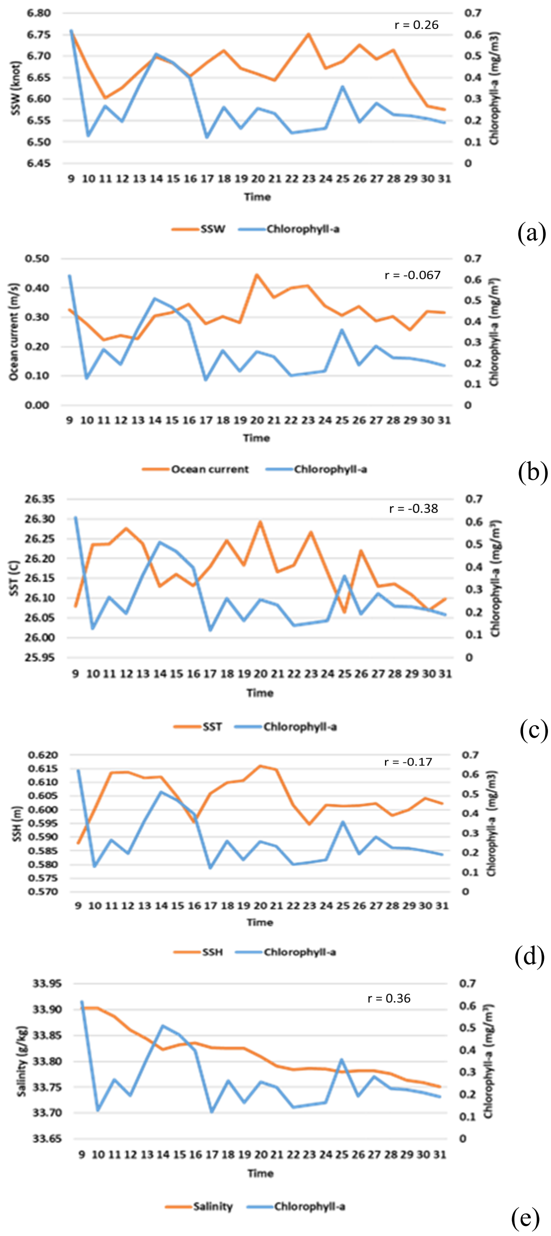


**Figure 4. Correlation between (a) SSW, (b) ocean currents, (c) SST, (d) SSH, and (e) salinity to CHL concentration.**

**Table 2. Comparison of CHL Climatology, Before, During, and After TC Marcus.**

| No | CHL | Climatology | Before | During | After |
|---|---|---|---|---|---|
| 1 | Mean (mg/m$^3$) | 0.23 | 0.36 | 0.21 | 0.24 |
| 2 | Maximum (mg/m$^3$) | 7.45 | 15.93 | 8.52 | 20.12 |
| 3 | Distribution (point) | 27192 | 19345 | 17529 | 25271 |

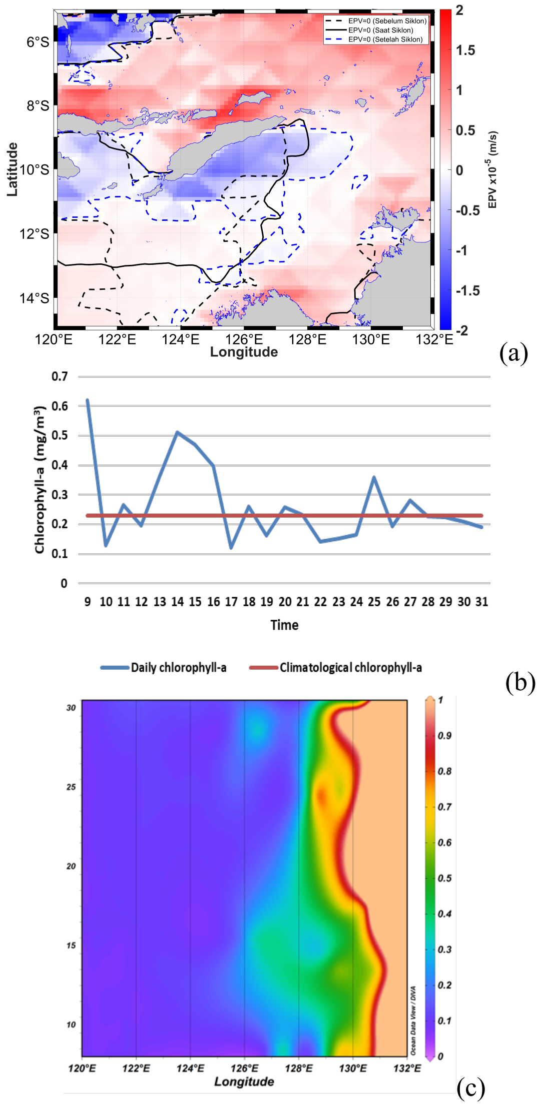


**Figure 5.** **(a) EPV before, during, and after the cyclone (b) Daily variations of CHL values from March 9 to March 31, 2018, compared to the 10-year average (2006 to 2015). (c) Hovmoller diagram of CHL (mg/m³) from March 9 to March 31, 2018.**

CHL concentration variations before, during, and after TC Marcus are summarized in Table 2. The CHL concentration before and after the occurrence of TC Marcus were higher than the CHL concentration average over the 10-year period. However, the CHL concentration average during the occurrence of TC Marcus were lower than the CHL concentration average over the 10-year period. The highest CHL concentration average is observed before the occurrence of TC Marcus. The maximum CHL concentration value was observed after the occurrence of TC Marcus, with a peak of 20.12 mg/m$^3$. The maximum concentration values before, during, and after the occurrence of TC Marcus are higher than the maximum average values over the 10-year period. The distribution average of CHL across the Timor Sea (spanning 120° E - 132° E and 10° S - 15° S) is 27192 points over the 10-year. The number of CHL distribution points of before, during, and after TC Marcus was below the CHL distribution average, however the number of distribution points after the occurrence of TC Marcus o was 25,721 points which was the nearest average value to the CHL distribution average across the Timor Sea.

Figure 5a shows the spatial distribution of the EPV parameter before, during, and after Tropical Cyclone Marcus in the Timor Sea and its vicinity. The red color represents positive EPV values indicating upwelling events, while the blue color represents negative EPV values indicating downwelling events. Black arrows represent the wind surface direction, while red arrows represent Ekman transport direction caused by the wind [28].

TC Marcus moved from the Timor Sea towards Southwest Australia as shown by the trajectory in table 1, resulting in the clockwise rotating winds formation at the cyclone's center. Clockwise rotating winds will generate currents beneath it and cause Ekman transport to move away from the cyclone center. This Ekman transport impacts the water mass beneath the cyclone center to diverge (voids), allowing deeper water to rise and fill the voids, this phenomenon known as upwelling. The spatial distribution pattern of EPV shown in Figure 5a aligns with the trajectory and phases of TC Marcus, with positive EPV values occurring beneath the cyclone's center. Positive EPV values at the center started to appear between 9$^{th}$ – 15$^{th}$ March and continued to increase from 16$^{th}$ – 24$^{th}$ March, as the cyclone intensified into a tropical storm. EPV values weakened and dissipated from 25$^{th}$ – 31$^{st}$ March. Figure 5a also shows that after the passage of TC Marcus (dashed black line), the upwelling region in the Timor Sea expanded compared to pre-cyclone period (dashed blue line). This difference only observed in the Timor Sea, while, there is as no change in the upwelling region were noted in the northern waters near NTT Island before, during, and after TC Marcus, suggesting that the passage of TC Marcus may have enhanced the productivity of the water it traversed.

Figure 5b shows there was a significant decrease in CHL concentration on the second day of TC Marcus, 17$^{th}$ March, reaching 0.12 mg/m$^3$, and begin to increase again once the TC Marcus dissipated on 25$^{th}$ March, 2018, reaching 0.35 mg/m$^3$. As seen in Figure

5b, during the TC Marcus from 17th to 24th March, 2018, the CHL concentration were below its 10-year average, except on 18th and 20th March, when concentration slightly exceeded the 10-year average of CHL concentration.

The Hovmoller diagram presented in Figure 5c was based on data collected at coordinates 12° S and 120 – 132° E. Within the range of 12° S and 120 – 126° E, the CHL concentration were relatively low and not significant, fluctuating from 0 to 0.2 mg/m$^3$ from March 9 to March 31, 2018. In contrast,at coordinates 12° S and 126 – 130° E, CHL concentration exhibited considerable variability, ranging from 0.1 to 1 mg/m$^3$. An increase in CHL concentration was observed at 129° E after the occurrence of TC Marcus, particularly on March 26, 2018. In the preceding days, from March 9 to March 24, 2018, the CHL concentration at the same coordinates ranged from 0.2 to 0.7 mg/m$^3$, and began to rose to 0.9 mg/m$^3$, on March 25 – 26, 2018. In the region between 12° S and 131 – 132° E, CHL concentration consistently exceeded 1 mg/m$^3$ due to the proximity to the coast, where cooler SST prevail, thereby reducing the influence of other parameters [29].

## 4. Conclusions

TC Marcus induces changes in oceanographic conditions along its trajectory. During the occurrence of TC Marcus, notable increase was recorded in wind speed, SST, ocean currents, salinity, and sea surface height, along with a decrease in CHL concentration. The reduction of CHL may also be attributed to increased precipitation associated with TC Marcus occurrence which introduced a substantial influx of freshwater around the Timor Sea. Otherwise, after TC Marcus, the oceanographic conditions in the Timor Sea exhibited a reversal of trends observed during the cyclone, including decreases in wind speed, SST, ocean currents, salinity, sea surface height, alongside a rise in CHL concentration. The shift in oceanographic dynamics conditions indicate the occurrence of downwelling during TC Marcus, followed by a transition to upwelling after Tropical Cyclone Marcus.

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