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Impacts of Tropical Cyclone Seroja on the Phytoplankton Chlorophyll-a and Sea Surface Temperature in the Savu Sea, Indonesia

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ABSTRACT Tropical cyclone (TC) Seroja was a rare climatic event in the Indonesian Seas, particularly in the Savu Sea. This unprecedented event, which occurred on April 4, 2021, caused fatalities and severe damage to the region's infrastructure and economy. High spatio-temporal resolution satellite measurements of surface winds (Cross-Calibrated Multi-Platform), surface chlorophyll-a (Himawari-8), and sea surface temperature (SST; RSS OISST) are used to disentangle the impact of extreme wind speed (> 10 m·s^{-1}) on chlorophyll-a and SST. High wind speed associated with TC Seroja induced strong upwelling and vertical mixing in the Savu Sea, which led to phytoplankton blooms and SST depression. An abrupt change of daily variability and positive anomaly in phytoplankton chlorophyll-a concentrations reaches 13 mg·m^{-3} and 0.3 mg·m^{-3}, respectively. At the same time, the SST shows significant cooling up to 3°C. Our results provide novel insights on the exceptional occurrence of a TC within the Indonesian Seas and highlight its impact on chlorophyll-a and SST.

INDEX TERMS Tropical cyclone Seroja, chlorophyll-a, sea surface temperature, Savu Sea.

I. INTRODUCTION

The effect of global climate change on the Indonesian Seas has been prominent during the last decade, mainly through tropical cyclones (TCs). Due to its proximity to the equator, the occurrence of TCs within the Indonesian Seas is quite rare [e.g., 1]. Nevertheless, several TCs have evolved in the ocean region adjacent to the Indonesian Seas, especially in the southeastern tropical Indian Ocean, like Anggrek (October 31 – November 4, 2010), Bakung (December 10 - 13, 2014), Cempaka (November 25 - 27, 2017), and Dahlia (November 27 – December 2, 2017) [2]–[6]. The two consecutive TCs, Cempaka and Dahlia, have caused catastrophic damages to life, the environment, and the economy [7]. A simulation study by [8] demonstrates that these TCs have significantly increased wave heights in the coastal regions of south Java and Lombok. According to [5], TC Dahlia has altered the thermal stratification of the upper ocean of the southeastern tropical Indian Ocean by lowering the SST (> 1.5°C). In addition to the effect of TCs on the oceans, some studies have revealed a positive correlation between a TC and an increase of chlorophyll-a concentration via upwelling and vertical mixing [8]–[13]. Though, based on the global model, most of the TCs do not induce chlorophyll-a bloom except in limited areas of the world ($\sim$1%), including northeastern Australia [14]. TC Seroja

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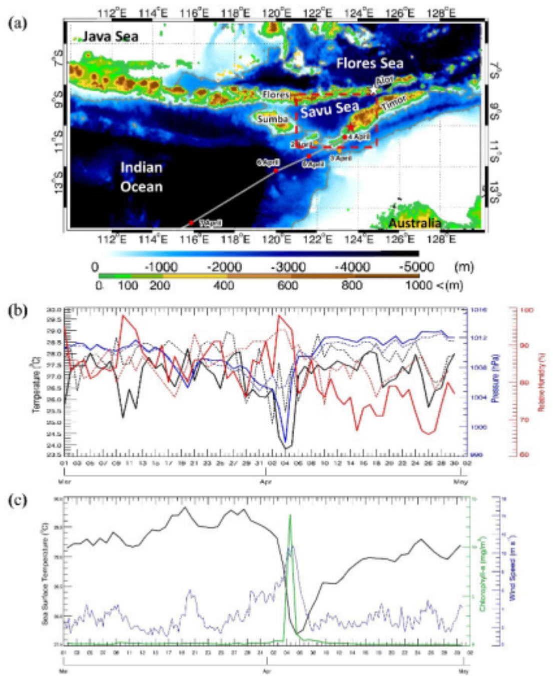

FIGURE 1. **(a) Map of the Savu Sea, bathymetry (m), land topography (m), and track of TC Seroja. The orange and red circles denote the early development stage and mature stage, respectively (b) Time series of air temperature (°C), relative humidity (%), and air pressure (hPa) at meteorological station at Kupang (red star) and Alor (Orange star), (c) Time series of SST, chlorophyll-a concentration, and wind speed of the Savu Sea (average area is 121 - 125° E; 8 - 11° S; red dash box).**

developed in southeastern Indonesia in one such limited region. Unfortunately, the effect of TCs on the phytoplankton chlorophyll-a concentration in the vicinity of the Indonesian Seas has been less examined, with the only study conducted by [6], hence an investigation on the relation between TCs and tropical primary productivity in the region is a top priority.

The Savu Sea is a semi-enclosed deep sea with a bathymetry of more than 1,000 m. As part of the Lesser Sunda Islands, the Savu Sea is surrounded by Flores Island, Alor Island, Timor Island, Rote Island, Savu Island, and Sumba Island [Fig. 1a]. The geographic position of the Savu Sea, which is located nearby the equator and enclosed by islands, theoretically makes the generation of TC impossible. TC could be generated only on the wide ocean between 10° - 20° N/S [15]. Nevertheless, on April 4, 2021, a TC called Seroja has formed within the Indonesian Seas and struck the Savu Sea with a maximum wind speed of about 80 km/h [16]. This unprecedented event has caused severe impacts and fatalities in the Lesser Sunda Islands and Australian regions. The consequence of TC Seroja on the Savu Sea and ocean region off the Lesser Sunda Islands remains elusive. Typically, the seasonal and interannual dynamics of the Savu Sea are affected by the Australia Indonesia Monsoon, Indonesian throughflow, and the El Niño-Southern Oscillation (ENSO), as well as the Indian Ocean Dipole (IOD) [17]–[22]. These climate events have played a prominent role in determining sea surface temperature (SST) and surface phytoplankton chlorophyll-a concentration in the Savu Sea and ocean region off the Lesser Sunda Islands [17], [19] [20], [22]. Specifically, the southeasterly winds during the Austral winter (June-September) generate significant SST cooling and increased chlorophyll-a due to an increase in Ekman transport, which enhances ocean surface productivity [20]. This condition is further intensified when the El Niño and the positive IOD occur at the same time. In contrast, during the Austral summer (December-February), the northwesterly winds induce an oligotrophic condition in the upper ocean due to the winds' favor downwelling. Intense downwelling events happen during the La Niña and the negative IOD [19], [20].

The Savu Sea has experienced extraordinary oceanographic and meteorological conditions due to the development of TC Seroja. In this research, we attempt to decipher the impact of TC Seroja on the phytoplankton chlorophyll-a concentration in the Savu Sea by analyzing high spatial and temporal resolutions of satellite-derived surface chlorophyll-a, SST, and surface wind. The present research is the earliest investigation on the evidence of elevated surface chlorophyll-a concentration within the Indonesian Seas generated by a TC.

II. MATERIALS AND METHODS

A. SURFACE WIND

To understand the physical forcing of TC Seroja, we analyzed the surface wind data obtained from the Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds version 2.0 for the period of 31 March-15 April 2021. This dataset can be downloaded from https://www.remss.com/measurements/ccmp/ (accessed on September 9, 2021). The CCMP used is a level-3 ocean wind vector product generated from various satellites, moored buoy, and model wind data. The surface wind data's temporal and spatial resolutions are six hourly and 0.25° × 0.25°, respectively. The accuracy of the CCMP is higher than the other wind reanalysis data [23]. We calculated the Ekman Pumping Velocity (EPV) by using the following formula [24]:

$$\tau = \rho_a C_d U_{10}^2 \tag{1}$$

where ρ_a is the density of air (1.25 kg m^{-3}), C_d is the drag coefficient, and U_{10} is the wind speed 10 m above sea level. We used an equation of [25] to determine the drag coefficient as follows:

$$1000C_d = 1.29 \quad \text{for } 0 < U_{10} < 7.5\text{m}\cdot\text{s}^{-1} \tag{2a}$$

$$1000C_d = 0.8 + 0.0065U_{10} \quad \text{for } 7.5 < U_{10} < 50\text{m}\cdot\text{s}^{-1} \tag{2b}$$

$$curl = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \tag{3}$$

$$EPV = -\frac{curl}{\rho_w f} \tag{4}$$

where f is the Coriolis parameter and ρ_w is the density of seawater calculated using an equation of [26]. The EPV's unit is m·s^{-1}.

B. SURFACE CHLOROPHYLL-A CONCENTRATION

The surface chlorophyll-a data employed in this research is a daily satellite image of the Himawari-8 Level 3 (https://www.eorc.jaxa.jp/ptree/) (accessed on June 3, 2021). The image has a spatial resolution of 5 × 5 km and a daily temporal resolution [27]. We will plot daily surface chlorophyll-a for the Savu Sea from March 1 to April 30, 2021, to depict the response of phytoplankton chlorophyll-a to TC Seroja.

C. SEA SURFACE TEMPERATURE (SST)

We analyzed the Optimally Interpolated (OI) SST daily products obtained from the Remote Sensing System (http://www.remss.com/ measurements/ sea - surface - temperature/) (accessed on September 9, 2021). Specially, we computed the 9 km microwave-infrared OI SST product, which has a daily temporal resolution, to discriminate the SST reaction to TC Seroja.

D. SEA LEVEL PRESSURE (SLP)

The hourly SLP data was obtained from the European Re-analysis (ERA) 5 produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) with a grid interval of 0.25° [28]. The data are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset / reanalysis-era5-single-levels?tab=form (accessed on June 3, 2021). The hourly data were averaged into daily data.

E. OBSERVATIONAL DATA

We used observational data from the weather stations operated by the Indonesian Agency of Meteorology, Climatology, and Geophysics (BMKG) at Kupang City and Alor Island as denoted by red and orange stars in Fig. 1a, respectively. The analyzed parameters were air temperature, relative humidity, and air pressure. Air temperature and air pressure data can be obtained from the National Centers for Environmental Information (NCEI) of the National Oceanic and Atmospheric Administration (NOAA), while the relative humidity data is available at https://dataonline.bmkg.go.id/ home.

In order to better understand the impact of TC Seroja on the ocean parameters above, we computed the daily anomaly of the wind speed, chlorophyll-a concentration, SST, and EPV from March 31 to April 15, 2021 to represent prior, during, and after the passages of TC Seroja. The period for climatological calculation was from 2015 to 2021.

III. RESULTS AND DISCUSSION

A. THE FORMATION OF TC SEROJA

Fig. 2 exhibits the development of the TC Seroja. On March 31, intense easterly winds appeared at the eastern

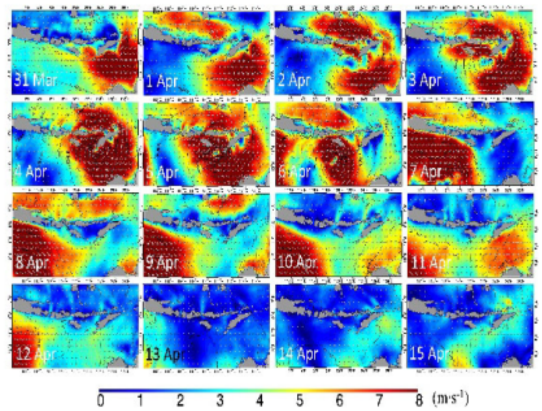

FIGURE 2. Anomaly maps of wind speed (m·s^{-1}) from March 31 to April 15, 2021.

Timor Island, followed by the formation of a depression zone at the eastern Timor and the Savu Sea on April 1 as denoted by low SLP by less than 1,005.2 hPa. On April 2, significant positive wind speed anomalies were observed in the Savu Sea, the Flores Sea, and the ocean region off northern Australia. Meanwhile, the depression zone shrinks and strengthens, forming a low-pressure system centered at the Savu Island. The low-pressure systems on April 2-3 generated a cyclonic wind pattern, which was the early developmental stage of TC Seroja. The translation speed of TC Seroja during this time was ~5.7 km·hr^{-1} (Table 1). TC Seroja was fully developed over the Savu Sea on April 4 and persisted until April 6 as denoted by the anomaly of cyclonic wind speed by more than 8 m·s^{-1} and low SLP by less than 1,000 hPa at the eye/core of TC. On April 7, TC Seroja moved southwestward with a translation speed between 18 and 22.1 km·hr^{-1}. From April 7 to 15, the Savu Sea was characterized by weak wind speeds. The track and translation speed of TC Seroja are summarized in Fig 1a and Table 1.

The formation of a low-pressure system cannot separate the generation of TC Seroja that occurred at the southern Savu Sea. The observational evidence of the formation of this low-pressure system is depicted by the variation of air pressure at the meteorological station at Kupang City, which is located nearby the center of TC Seroja (Fig. 1b). On March 21, the air pressure started to decrease and drop, indicating the early development stage of TC Seroja. The lowest air pressure occurred on April 4, reaching 998 hPa at the mature stage of TC Seroja. After that, the air pressure increased along with the southwestward movement of TC Seroja leaving the Savu Sea. The drop of air pressure before TC Seroja may correspond to the rise of relative humidity. As the relative humidity increased, the air became lighter, reducing the air pressure. In contrast, the air temperature may play a pivotal role as the impact of TC Seroja was robust since the air temperature decreased (increased) following the decline (acceleration) of air pressure before (after) the mature stage

TABLE 1. The translation speed of TC Seroja and statistics of the investigated parameters.

Date	Distance (km)	Velocity ($km{\cdot}hr^{-1}$)
2-3 April 2021	137.4	5.7
3-4 April 2021	82.1	3.4
4-5 April 2021	217.6	9.1
5-6 April 2021	191.4	8
6-7 April 2021	529.3	22.1
7-8 April 2021	454.3	18.9

Parameter	Mean	Standard Deviation
Wind speed ($m{\cdot}s^{-1}$)	3.3	1.7
SST (°C)	29.1	0.4
Chlorophyll-a ($mg{\cdot}m^{-3}$)	0.4	1.6
EPV ($m{\cdot}s^{-1}$)	3.7	69.2

of the cyclone. The increasing wind speed (Fig. 1c) and the decreasing air pressure during the development of TC Seroja may cool the surface air temperature. The same indication is also found in the Alor meteorological station, which TC Seroja also impacted. The decrease (increase) of air pressure before (after) the mature stage of TC Seroja corresponded to the increase (decrease) of the relative humidity in the lower amplitude. Furthermore, the importance of humidity for TC generation has been well simulated by previous studies, e.g. [29]–[31]. TCs develop more quickly and become more intense in a moist environment [29]. A simulated TC during dry environmental conditions exhibits reduced precipitation outside TC core, a narrower potential vorticity distribution, and reduced lateral extension of the wind field relative to storms in more moist environments [30]. Thus, the increase of relative humidity from March 29 to April 4 may play a vital role in developing TC Seroja, which is theoretically difficult to form in this area. Further analysis is needed to prove this hypothesis. Moreover, the formation of the low-pressure system may also correspond to the SST warming, which is observed in the Savu Sea from March 1 to 29 (Fig. 1c). The peak of SST warming reached 29.8°C on March 20 and 29. This warm SST may induce air temperature warming, which reduces SLP. However, the detail of TC Seroja formation is beyond the present research's scope, which focuses on the impact of TC Seroja on the variability of chlorophyll-a and SST in the Savu Sea. This task will be explored in our future study.

B. THE EFFECT OF TC SEROJA ON THE CHLOROPHYLL-A AND SST IN THE SAVU SEA

The analyses of surface wind speed and chlorophyll-a anomalies (Fig. 2 and 3) demonstrated that the strong winds associated with TC Seroja are the primary forcing for the positive anomaly of phytoplankton chlorophyll-a concentration (~3 $mg{\cdot}m^{-3}$) in the Savu Sea as well as in the adjacent seas from April 6 to 12 (Fig. 3). The absence of chlorophyll-a concentration data from April 1 to 5 was mainly due to cloud cover over the studied area. Fig. 2 shows a strong wind anomaly (> 9 m·s-1) in the Savu Sea with its most significant spatial extent on April 4-5. During normal conditions, monsoon winds do not favor a phytoplankton chlorophyll-a bloom in the region. A robust effect of TC Seroja winds is also apparent on the SST anomaly as there is a prominent SST decline (up to 3°C) in the region of interest at the same period (Fig. 4). Thus, in the early development of TC Seroja, the warmer SST contributed to the development of TC, but then when the TC was fully developed, the SST was impacted by the TC. Indeed, our novel results provide robust evidence on the consequence of TC Seroja on the sea surface due to the position and timing of the strong winds are congruent with the location and timing of the phytoplankton chlorophyll-a blooms and SST depressions. TC Seroja likely triggered the injection of nutrients from the deeper layer to the euphotic layer, possibly via upwelling and mixing, which led to primary productivity enhancements of the ocean surfaces of the Savu Sea and its surrounding sea. Daily observation of the three parameters in the Savu Sea also shows good conformity, suggesting TC Seroja wind (> 10 $m{\cdot}s^{-1}$) is the primary driver for the phytoplankton chlorophyll-a maximum (> 12 $mg{\cdot}m^{-3}$) and SST minimum (< 28°C) in the Savu Sea (Fig. 1c). The rapid chlorophyll-a fluctuation may also be related to the translation speed of TC Seroja (Table 1). From April 2 to 3, the translation speed was 5.73 $km{\cdot}hr^{-1}$. Then from April 3 to 4, when the wind speed reached maximum over the Savu Sea, the translation speed was only 3.42 km/hr. The strong wind persisted longer in the Savu Sea, which then effectively generated nutrient enrichment. Moreover, since the Savu Sea is semi-enclosed, this escalating nutrient was not flushed away by current as usually occurs in the open ocean. The large (weak) changes of SST and chlorophyll-a associated with typhoons correspond to the high (low) wind speeds and slow (fast) translation speeds [13].

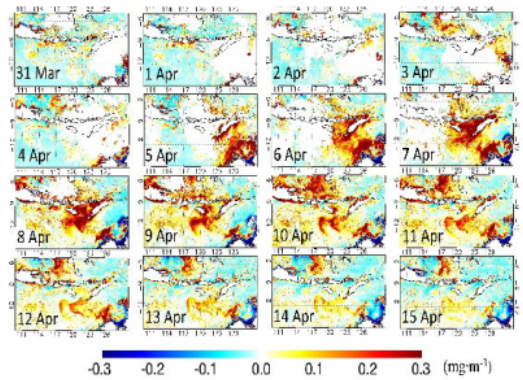

FIGURE 3. Anomaly maps of phytoplankton chlorophyll-a concentration ($mg{\cdot}m^{-3}$) from March 31 to April 15, 2021.

Fig. 1c inarguably suggests the abrupt change in phytoplankton chlorophyll-a concentration is a direct ocean

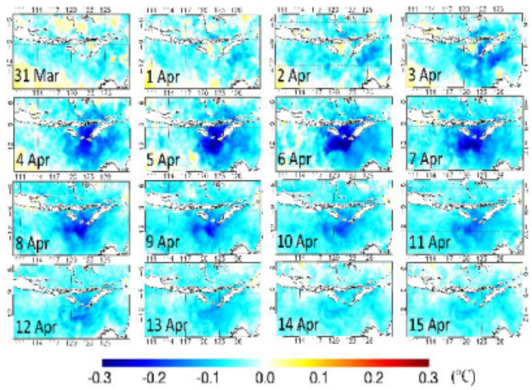

FIGURE 4. Anomaly maps of SST (°C) from March 31 to April 15, 2021.

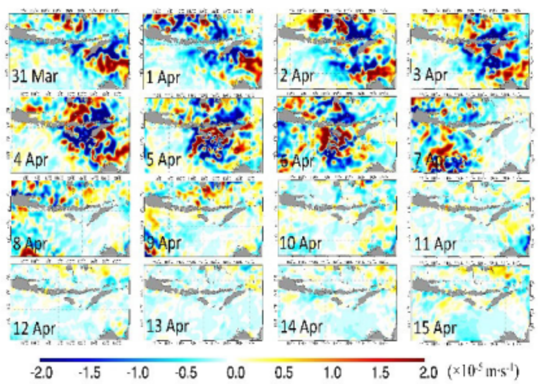

FIGURE 5. Anomaly maps of EPV ($m \cdot s^{-1}$) from March 31 to April 15, 2021.

surface response to TC Seroja-induced upwelling and mixing in the Savu Sea. The increased chlorophyll-a during TC Seroja was significantly greater compared to Cempaka and Dahlia Cyclones (November 25 to December 2, 2017) in the southern Java of the Indian Ocean. The chlorophyll-a maximum during Cempaka and Dahlia Cyclones was only $0.16\ mg \cdot m^{-3}$ [6]. Thus, the present study demonstrates an extreme chlorophyll-a bloom as a result of a TC occurrence in a semi-enclosed sea. However, noting that the chlorophyll-a data is retrieved from the visible bands, which are limited during heavy cloudy conditions under TC occurrences, the chlorophyll-a on April 4 in Fig. 1c is obtained only based on the mean value of seven grids within the dashed red box depicted in Fig. 1a.

The EPV anomaly analysis, as illustrated in Fig. 5, delineates convincing evidence on the episodes of upwelling due to TC Seroja. Negative EPV anomalies suggest upwelling, with the most substantial upwelling, occurred on April 4. Interestingly, although the EPV anomaly values were usually zero from April 7 to 11, the ocean surface of the Savu Sea was still dominated by positive anomalies of phytoplankton chlorophyll-a concentration (up to $0.3\ mg \cdot m^{-3}$) and negative SST anomalies (up to $-3°C$) during this time frame. It is unlikely that the positive anomaly of phytoplankton chlorophyll-a concentration resulted from wind mixing and terrestrial nutrient input because the wind showed a low speed and seasonally nutrient fluxes from the continental runoff into the Savu Sea are negligible [16]. Instead, we postulate that it resulted from vigorous upwelling that can substantially uplift the nutricline and thermocline, which led to increases in phytoplankton chlorophyll-a concentrations after the passage of TC Seroja. The abundance of nutrients in the Savu Sea after the passage of TC Seroja may indicate that the phytoplankton needs time to grow. It is difficult to quantify the contribution of upwelling and mixing in perturbing the upper ocean structure in the present research as the Savu Sea lacked long-term in situ measurement. Thus, it is noteworthy to investigate such disturbance in future studies using the ocean model. A diagnostic analysis of observational and simulation data would give insight into TC Seroja on the vertical profile of the Savu Sea, as TC Seroja may have significantly impacted biogeochemical processes like carbon fixation [32], [33].

IV. CONCLUSION

In the present research, the impacts of TC Seroja on phytoplankton chlorophyll-a concentration and SST in the Savu Sea were investigated using satellite remote sensing data. The formation of TC Seroja was well captured by satellite-derived surface wind speed. The early development of TC Seroja was started on April 2 and peak on April 4. A low-pressure system was formed during the development of TC Seroja and possibly was influenced by an increase in the relative humidity within the study area. The effect of the TC Seroja was also accurately documented by satellite-derived surface chlorophyll-a concentration and SST. Daily variations and anomalies of surface wind, chlorophyll-a concentration, SST, and EPV show a robust congruency. The strong wind associated with TC Seroja was a predominant driving force for the phytoplankton chlorophyll-a maxima and SST cooling in the Savu Sea, perhaps via upwelling and water column mixing. The extent that upwelling and mixing deteriorates water column stratification of the Savu Sea be investigated in our future research using numerical simulation. Nevertheless, our results can be used as a reference for future studies concerning the impact of TC on the Indonesian Seas.

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