Ocean Response to Tropical Cyclone Seroja at East Nusa Tenggara Waters

Avrionesti¹, Faruq Khadami²,³, Dayu W. Purnaningtyas⁴,³

¹ Marine Technology Cooperation Research Center
² Department of Civil and Environmental Engineering, Graduate School of Engineering, Hiroshima University
³ Oceanography Research Group, Faculty of Earth Science and Technology, Institut Teknologi Bandung
⁴ Marine Ecosystem Research Center, Korea Institute of Ocean Science and Technology

avrionesti@mtcrc.center

Abstract. Tropical Cyclone (TC) Seroja is a unique tropical cyclone that has significant impacts along its path, such as floods in East Nusa Tenggara and high waves along the southern coast of Indonesia. Research related to ocean responses to tropical cyclones in Indonesia is still limited due to its rarely occurrence in Indonesian waters. The responses of the upper ocean to TC Seroja were investigated using multi-satellite remote sensing of sea surface wind (SSW), sea surface temperature (SST), sea surface height anomaly (SSHA), and numerical model of mixed layer depth (MLD) and chlorophyll-a (Chl-a). The SST cooling occurred around the TC Seroja track at 0.5 – 3°C after the storm had passed. During April 3 – 7, 2021, in addition to spatial SST cooling, changes in chlorophyll-a, SSHA, and MLD were also detected. The chlorophyll-a increase to 2.57 mg/m³ and SSHA reached -10 cm. Thus, the MLD was deeper around the eye of the storm during the cyclone and became uniform after the storm passed. These characteristics indicate the upwelling phenomenon induced by the cyclone.

1. Introduction
In general, tropical cyclone formation occurs over a warm ocean in areas within 10° to 20° from the equator and does not occur below 4° from the equator [1,2]. Tropical cyclone activity in the southern Indonesia region primarily occurs between February to April[3]. Therefore, Indonesian territory is barely surpassed by tropical cyclones. This makes Tropical Cyclone (TC) Seroja a unique cyclone. Several other cyclones that have affected the territory of Indonesia include tropical cyclones Vamei (2001), Rosie (2008), Cempaka (2017), Dahlia (2017), Flamboyan (2018), and Kenanga (2018)[3,4]. On the 3rd of April 2021, the Meteorology, Climatology, and Geophysics Agency of Indonesia (BMKG) reported the formation of the tropical cyclone Seroja in East Nusa Tenggara. Tropical cyclones continued to develop and form a vortex on April 5, 2021. Cyclone Seroja left a devastating impact, with 182 deaths recorded, 47 missing, and 84,876 others evacuated[5,6]. The Indonesian government enforced the emergency status from April 6 to May 5, 2021, and was stated in Decree Number 118/KEP/HK/2021[6].
Besides having an impact on coastal areas, cyclones also affect offshore areas. The ocean's response to cyclones can be seen in changes in currents, waves, sea surface height, salinity, temperature, nutrients, and chlorophyll [7,8]. These extreme changes trigger another phenomenon called upwelling, which causes the vertical movement of nutrient-rich water masses to the surface layer. This increase in nutrients is an indicator that can be used to determine the fertility level of an ocean area. Strong enhancement of chlorophyll-a concentration occurred in response to Typhoon Hagibis (2007). The cyclone had a horizontal ‘V’-type track and had a long forcing time (>82 h) induced strong upwelling in the middle of the South China Sea. The mixed layer depth surrounding the cyclone area deepened to 25 m. The chlorophyll-a concentration increased by approximately 30% of the total annual chlorophyll-a [7].

Cyclonic upwelling is slightly different from coastal upwelling. In coastal upwelling, the MLD becomes shallower along the coast[9]. However, in cyclonic upwelling, the change in the MLD can be negative or positive depending on the area under. The affected area experiences a deepening of the MLD, but the MLD will be shallow in the center of the storm. Cyclone Hagibis deepened the MLD by approximately 25 m based on the Argo float, which is located in the west of the cyclone[7]. In contrast, the upper ocean response to TC Tembin found that the MLD was uplifted by 25 m. Cyclones usually deepened the MLD, but the Super TC Tembin since the Argo float was very close to the center of the TC (~ 35 km)[10]. Moreover, the tropical cyclone footprint in the ocean mixed layer in the Northwest Pacific based on data from Argo profiles during 1998–2011 shows that the MLD is on average 5 m thick, although spatially there are areas that experience MLD shallowing[11].

Several researchers have also investigated the upper ocean response to TCs that occur around Indonesian waters. Numerous studies have reported that high waves, increases in high sea level anomalies, and storm surges were recorded in Indonesian coastal areas as responses of tropical cyclones. [12–14]. TC Nicholas (11–20 February 2008) affected Indonesian coastal by the surge residual values ranging from 11 to 38 cm and has time lag to the cyclone about 0.71–5.75 days [12]. TC Jacob (2–12 March 2007) and TC George (3–9 March 2007) in northwestern Australia induced storm surge at coastal areas of the southern part of Java while Nusa Kambangan experienced the highest surge among the other stations, about 0.19m [13]. The impact of TC Cempaka and Dahlia also investigated using numerical modeling and altimetry satellite. During the TCs, the wave height in Indian Ocean increased up to >2 meters with the highest percentage of sea wave height increase occurs in Pelabuhan Ratu Port, up to 1028.31% from normal conditions. Meanwhile, significant wave height from numerical model has smaller value than the altimetry satellite [14]. Therefore, when TC Quang passed in Indonesia on April 2015, the concentration of chlorophyll also increased as the upwelling occurred[15]. Another phenomenon was observed in the Arafura Sea on April 28, 2017, where the TC Frances’ wind speed reached 24-28 knots and moved to the northwest of Darwin. Daily composite of chlorophyll-a concentration showed the area surpassed by TC Frances experienced a different increase of chlorophyll-a concentration, between 0.4 mg/m³ – 5.0 mg/m³[1,16]. In general, the upwelling of tropical cyclone Frances was categorized as weak to moderate upwelling based on the criteria in Table 1[1]. Through this research, the author wants to see the effect of TC Seroja on the upper ocean in the East Nusa Tenggara Waters area.

### Table 1. Upwelling Intensity Criteria [1]

| Sea Surface Temperature (°C) | Chlorophyll-a (mg/m³) | Categori upwelling |
|-----------------------------|-----------------------|--------------------|
| > 27                        | < 1                   | Weak               |
| 26 – 27                     | 1 – 2                 | Moderate           |
| < 26                        | > 2                   | Strong             |
2. Data and Methodology

In this study, the atmospheric and oceanic parameters were investigated using sea surface wind, sea surface temperature (SST), chlorophyll-a, mixed-layer depth (MLD), and sea surface height anomaly (SSHA) data along the Nusa Tenggara waters (7-15°S, 114-129°W) from April 1 to 10, 2021. The initial state before the cyclone occurred was represented by the parameter conditions on the 1st and 2nd of April 2021. Then, the ocean state during the cyclone was represented by parameter conditions on April 3rd – 7th of April, and the post-cyclone state was represented by the parameter condition on 8th – 10th April, 2021.

The daily sea surface wind was plotted based on the Advanced SCATterometer (ASCAT) METOP satellite[17]. SST data were derived from Advanced Very High Resolution Radiometers (AVHRRs) SST Level-4 product, Copernicus Climate Data Service[18]. Meanwhile, the origin of chlorophyll and mixed layer depth were from E.U. Copernicus Marine Service Information (CMEMS) - Global Monitoring and Forecasting Center [19]. The mixed layer depth data is a product from CMEMS that is calculated from the minimum temperature threshold equivalent to a 0.2°C decrease. To review the effect of cyclones on SSHA, weekly SSHA changes were used. The pre-cyclone condition was represented by SSH 15-31 March 2021, while the cyclone stage was represented by SSH 1-7 April 2021, and the post-cyclone condition was represented by SSH 8 – April 14, 2021. The weekly SSHA value was obtained by subtracting the weekly SSH data from the average weekly SSH data from 1993-2019.

3. Results

![Figure 1. Tracks of TC Seroja (left). Zoom of blue box (right)](image)

Tropical cyclone Seroja began to become a tropical depression on April 3, 2021, with wind speeds reaching 54 km/h. On April 5, 2021, the eye of a cyclone began to form when the wind speed reached 76 km/h. When it became a tropical cyclone, the TC Seroja was in the East Nusa Tenggara Waters and moved closer to the Australian continent. The cyclone had a life span of approximately 10 days since it formed as a tropical depression and disappeared on April 12, 2021, in western Australia. Cyclone Seroja collided with cyclone Odette on April 9, 2021, which changed its direction and formed a larger cyclone (Figure 1). Owing to the significant difference in pressure in the area around tropical cyclones, these areas have quite strong wind speeds. The surface wind conditions of the study area are shown in Figure 2.
The sea surface wind in south of Timor Island on April 1, 2021, before TC Seroja occurred, was blowing from the east with an average speed of approximately 10 m/s. When the TC Seroja forms a tropical depression on April 3, 2021, the sea surface wind conditions are already quite strong, which is approximately 11 – 15 m/s. Wind conditions generally strengthen along with the development of tropical cyclones where when tropical cyclones enter on a scale of 2, surface wind speed exceeds 25 m/s (76 km/h or 48 knots) with the eye of the storm located in the southern part of the Savu Sea (Figure 1).

The ocean response to cyclones can also be observed from the changes in SST, MLD, and SSHA. Figure 2 represents the spatial SST in the study on April 1 – 10, 2021. The cyclone from southern Timor Island moved to the southwest on April 3 and left the study area on April 7, 2021. In the figure, we can see that SST in the Savu Sea slowly decreases during April 1 – 6, 2021. The average SST at the initial state on April 1 was 29.72°C. The average SST decreased to 29.21°C on April 6, 2021, and rose again to 29.58°C on April 10, 2021, with the lowest temperature recorded on April 6, 2021 (26.32°C). This occurred in line with the direction of the cyclone track that moved away from the East Nusa Tenggara waters.

Figure 2. Sea Surface Wind (a-j) and Sea Surface Temperature (k-t)
Another phenomenon related to cyclone events is upwelling. It can be determined by the changes in chlorophyll concentration, SST, MLD, and SSHA. The main effect of upwelling was an increase in the concentration of chlorophyll in the affected region. In Figure 3, compared to the initial state on April 1, 2021, the concentration in the Southern Savu Sea of chlorophyll-a increased on April 3, 2021, and reached its peak on April 7, 2021, reaching a concentration of 2.57 mg/m$^3$. On April 10, 2021, the chlorophyll concentration was still monitored, but it decreased to 0.58 mg/m$^3$.

Cyclones also affect the depth of the mixed layer. On April 1, 2021, it was shown that the mixed layer varied spatially. On April 3, 2021, MLD shallowing on the southern coast of the island of Timor began to be seen, accompanied by deepening on the northern coast of Australia. In contrast to coastal upwelling events, cyclonic upwelling caused MLD to shallower at the center of the cyclone and deepened the MLD around the cyclone. This can be seen clearly in the MLD pattern on April 5-7, 2021, especially on April 7, 2021. Then, the cyclonic pattern began to fade on April 8, 2021. The shallowest MLD on the TC track reached 10 m, and the deepest MLD reached 60 m. After the cyclone, the mixing effect was still captured as an almost uniform MLD in the study area on April 10, 2021, with an average MLD of 12.23 m.
The initial conditions of the SSHA are depicted in Figure 4a, where the offshore SSHA tends to be positive compared to the nearshore. During the cyclone, the offshore SSHA changed drastically from +10 cm to approximately −10 cm. A decrease in SSHA (up to −10 cm) was found in line with the direction of the TC Seroja, which was similar to the slight SST cooling described in Figure 2. Even the post-cyclone SSHA on the track of the TC decreased up to −15 cm. The changes in all parameter values that have been described previously strengthen the indications for cyclonic upwelling due to TC Seroja in the study area.

In the upwelling generated by the TC Seroja event, an abundance of chlorophyll-a was significantly recorded during the TC passed until 1-2 days after the TC passed. The period of upwelling is different from the seasonal upwelling generated by the easterly monsoon. The seasonal upwelling on Lesser Sunda Island occurred in June – October, and the abundance of chlorophyll-a prevails for 1-2 months[20]. The difference in the upwelling duration was due to the different forcing mechanisms. Seasonal upwelling in the Lesser Sunda Islands is a coastal upwelling induced by easterly monsoon winds from June to October. For the TC Seroja events, upwelling is generated by a cyclonic wind that causes vertical movement of the water mass. Therefore, seasonal upwelling is modulated by the Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO), in which upwelling strengthens during IOD positive and La Niña where the thermocline is shallowing[21]. However, the modulation of remote forcing (IOD/ENSO) to the intensity of upwelling generated by TCs is still unclear and requires further study.

4. Conclusion
Upwelling occurred in response to the Tropical Cyclone Seroja. This upwelling was determined by the increase in chlorophyll-a, decreased SST and SSHA, and shallowed MLD in the eye of the storm. The SST cooling occurred around the TC Seroja track at 0.5 – 3 °C after the storm had passed. The chlorophyll reached 2.57 mg/m³, SSHA decreased up to -10 cm, and the MLD shallowest part reached 10 m.

Understanding the generation of upwelling induced by TC in this area is essential for improving the knowledge of ocean dynamics in the southeastern Indian Ocean. However, in this study, we limited the analysis to the responses of the seas during the TC event without considering seasonal variability and remote forcing modulation. In reality, these variabilities have a significant role in ocean dynamics, particularly in the south of Lesser Sunda Island. Therefore, further study of upwelling generated by TC that considers seasonal and modulation of remote forcing is needed as an extension of this study.

Figure 4. The SSHA Before (a), During (b), and After (c) TC Seroja occurred
References

[1] Gaol A L, Siadari E L, Ryan M and Kristianto A 2019 Dampak Siklon Tropis Frances Terhadap Upwelling Laut Timor Dan Sekitarnya J. Meteorol. Klimatologi dan Geofis. 5 37–45
[2] Kuttippurath J, Sunanda N, Martin M V., and Chakraborty K 2021 Tropical storms trigger phytoplankton blooms in the deserts of north Indian Ocean npj Clim. Atmos. Sci. 4 1–12
[3] Musim Siklon di Sekitar Indonesia nd, viewed 31 June 2021, <http://tcwc.bmkg.go.id/siklon/learn/06/id>
[4] Australian tropical cyclone season outlook archive nd, viewed 31 June 2021, <http://www.bom.gov.au/climate/cyclones/australia/archive.shtml>
[5] Siklon Tropis dan Dampak Badai Seroja yang Ekstrem di NTT 2021, viewed 27 June 2021, <https://nasional.kompas.com>
[6] Lebih Dari 84 Ribu Jiwa Masih Mengungsi Akibat Siklon Tropis Seroja 2021, viewed 27 June 2021 <www.voaindonesia.com>
[7] Sun L, Yang Y J, Xian T, Lu Z M and Fu Y F 2010 Strong enhancement of chlorophyll-a concentration by a weak typhoon Mar. Ecol. Prog. Ser. 404 39–50
[8] Zhang H, He H, Zhang W Z and Tian D 2021 Upper ocean response to tropical cyclones: a review Geosci. Lett. 8 1–12
[9] Radjawane I M, Nurdjaman S and Apriansyah 2015 Seasonal variability of mixed layer depth in Indonesian Seas AIP Conf. Proc. 1677
[10] Guan S, Liu Z, Song J, Hou Y and Feng L 2017 Upper ocean response to Super Typhoon Tembin (2012) explored using multplatform satellites and Argo float observations Int. J. Remote Sens. 38 5150–67
[11] Fu H, Wang X, Chu P C, Zhang X, Han G and Li W 2014 Tropical cyclone footprint in the ocean mixed layer observed by Argo in the Northwest Pacific J. Geophys. Res. Ocean. 119 8078–92
[12] Ningsih N S, Hanifah F, Tanjung T S, Yani L F and Al Azhar M 2020 The Effect of Tropical Cyclone Nicholas (11–20 February 2008) on sea level anomalies in Indonesian waters J. Mar. Sci. Eng. 8 1–17
[13] Ningsih N S, Hadi S, Utami M D and Rudiawan A P 2011 Modelling of storm tide flooding along the Southern Coast of JAVA, Indonesia Adv. Geos. Vol. 24 Ocean Sci. 87–104
[14] Windupranata W, A.D.S. Nusantara C, D. Wijaya D and Prijatna K 2019 Impact Analysis of Tropical Cyclone Cempaka-Dahlia on Wave Heights in Indonesian Waters from Numerical Model and Altimetry Satellite KnE Eng. 2019 203–14
[15] Haryanto Y D, Fadlan A, Hartoko A, Anggoro S and Zainuri M 2017 Dampak siklon tropis quang terhadap tinggi gelombang, arus laut dan upwelling di perairan selatan jawa J. Meteorol. Dan Geofis. 45–54
[16] Tropical Cyclone Frances nd, viewed 1 July 2021, <www.ausstormscience.com/tropical-cyclones/te-frances/>
[17] Bentamy Abderrahim, Croize-Fillon D 2012 Gridded surface wind fields from Metop/ASCAT measurements. International Journal of Remote Sensing, 33(6), 1729-1754. doi:10.1080/01431161.2011.600348
[18] Vermote E., NOAA CDR Program 2019 NOAA Climate Data Record (CDR) of AVHRR Surface Reflectance, Version 5. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V53776Z4. Accessed 14 June 2021
[19] Staneva J, Behrens A, Ricker M, and Gaye G 2020 Black Sea Waves Analysis and Forecast (CMEMS BS-Waves) (Version 2). Copernicus Monitoring Environment Marine Service (CMEMS). doi.org/10.25423/CMCC/BLKSEA_ANALYSISFORECAST_WAV_007_003. Accessed 14 June 2021
[20] Ningsih N S, Rahmaputeri N and Harto A B 2013 Upwelling variability along the southern coast of Bali and in Nusa Tenggara waters Ocean Sci. J. 48 49–57
[21] Susanto R D, Gordon A L and Zheng Q 2001 Upwelling along the coasts of Java and Sumatra and its relation to ENSO Geophys. Res. Lett. 28 1599–602

Acknowledgement
This research was a part of the project titled “Marine Science & Technology Cooperation between Korea and Indonesia (20180319)” and “Ocean and Coastal Basic Survey and Capacity Enhancement in Cirebon, Indonesia (G52440)” funded by the Ministry of Oceans and Fisheries, Korea. The data were obtained from the Centre de Recherche et d'Exploitation Satellitaire (CERSAT), at IFREMER, Plouzané (France) and E.U. Copernicus Marine Service Information data.