Nutrient enrichment induced by tropical cyclone Seroja in the southeastern tropical Indian Ocean

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Abstract. Tropical cyclone (TC) passage triggers a complex response from the adjacent ocean, including vertical mixing, leading to biochemical alterations and affecting the surrounding ecosystem’s dynamics. In previous studies, increased nutrient concentrations and primary production were observed along the cyclone track after the storm. TC Seroja was awakened near the equator in the southeastern tropical Indian Ocean, making it interesting to investigate how the ambient ecosystem responds. Hence, we analyzed the sea surface temperature and nutrient changes during the Seroja event using multi-satellite remote sensing and numerical model data in the south of Indonesia and East Timor along the Seroja track between April 2 and 10, 2021. Immediately after the TC Seroja passed, the sea surface temperature cooled to 3 °C around the TC lane. At the same time, the spatial distribution patterns showed the upsurge of some nutrients in response to the passage of TC Seroja; the surface nitrate swells up to 1.5 mmol/m3, while phosphate increased up to 0.2 mmol/m3, and the dissolved silicate concentration enhanced up to 1.0 mmol/m3. The responses recover within 2-7 days. These results indicate that tropical cyclones contribute to nutrient enrichment in oligotrophic areas outside of their usual annual upwelling time, thereby further supporting ecosystem sustainability.

1. Introduction

Tropical cyclones, known as typhoons or hurricanes, are natural phenomena involving air-sea interactions. Complex responses are generated under the sea, such as strong mixed layer currents, upwelling, internal waves, and biochemical modifications, which may disturb the stability of the environment and communities [1][2]. Although tropical storms cause damage to their surroundings, some researchers have found several positive effects after the typhoon passed [3]. Most of the previous studies discussed the phenomenon of nutrient enrichment and high primary productivity in response to cyclones.

Generally, nutrient concentration in seawater can be enriched by several processes, including atmospheric disposal, river runoff, and annual upwelling events, which bring the deposited biomass from the seabed to the surface water [1][4]. The yearly upwelling in tropical areas is influenced mainly by the monsoon system [5]. Occasionally, the upwelling phenomenon could also be generated by
tropical cyclones. From this point of view, TC could be one of the natural catastrophic events that participated in the sustainability of the marine ecosystem related to the provision of feedstocks.

On April 4, 2021, an unusual tropical cyclone (TC Seroja) woke up near the equator zone around the southern coast of Nusa Tenggara waters, Indonesia. The region is a vital habitat for Southern Bluefin Tuna (SBT), especially during the reproductive cycle, and annual upwelling characteristics from June to October [6][7]. Studies on cyclone effects are widely carried out in the Northern Indian Ocean, while the southern part is minimal, even though the area has many potential ecosystems affected by the storm. Therefore, the investigation of the influence of TC Seroja on the marine environmental response has become more interesting. Moreover, previous studies have shown that global warming contributes to increasing tropical cyclone intensity and translation speed [8]. To assess the chemical responses to the cyclone in this area, we observed the nutrient changes before, during, and after the TC Seroja passed. The investigation was conducted using multi-satellite remote sensing and numerical model data in the south of Indonesia and East Timor along the Seroja track between April 2 and 10, 2021.

2. Methodology
In the current study, the alteration of the ocean environment induced by TC Seroja was investigated using sea surface temperature (SST) and nutrient data along the southern coast of the Bali and Nusa Tenggara waters (7°S to 15°S and 114°E to 129°E, as shown in Figure 1) from April 2 to 10, 2021. The SST data were derived from the C3S SST L4 product of the Copernicus Climate Data Service. Meanwhile, nutrient data (nitrate, phosphate, and silicate) originated from E.U. Copernicus Marine Service Information (CMEMS) - Global Monitoring and Forecasting Center. Data visualization was performed using MATLAB.

![Figure 1. Tracks of TC Seroja; the region of interest (7-15°S, 114-129°E). TC's wind speed is described with coloured lines.](image-url)
3. Result

3.1. SST changes during the cyclone Seroja

Remote sensing data have been widely used in studies of the ecological response of water bodies to tropical cyclones [9]. The 9-day composite SST maps are depicted in Figure 2. The two maps in the first column (a, b) refer to the day before the passage of Seroja, those for figure c and in the second column (d, e, f, g) refers to the day when the cyclone was nearest to the observed region, and those in the third column (h, i) refer to the day after the passage of the storm, respectively.

The SST was altered by the TC Seroja and significantly dropped up to 3 °C compared with before the cyclone. As shown in Figure 2, the SST in most of the cyclone-influenced areas decreased after the storm. The SST begins to drop a couple of days before the storm passage, usually reaches its minimum one day after the path, and then gradually recovers to its climatologically normal state [10][11][12][13]. In this study, the SST experienced began to drop on April 3 and reached a minimum on April 6 when the Seroja's wind speed increased up to 90 km/h, then gradually recovered after that day.

![Figure 2](image-url)

**Figure 2.** Sea surface temperature profiles before TC Seroja on 2-3 April (a,b), during TC Seroja on 4-8 April (c, d, e, f and g) and after TC Seroja on 9-10 April (h, i).

3.2. Nutrient enrichment induced by cyclone passage

The concentrations and variation patterns of nutrients in the study area were considerably changed by the passage of Seroja (Figure 3). Greater nutrient concentration changes occurred at the surface just after Seroja passed the region. The surface nitrate, phosphate, and silicate concentrations were elevated on April 4, especially on the southern coast of Sawu and Rote Islands, compared with July 2 (Figures 3). The surface nitrate swells up to the maximum concentration of 1.5 mmol/m3, while phosphate increases up to 0.2 mmol/m3, and the dissolved silicate concentration is enhanced up to 1.0 mmol/m3 on 6 April (Figures 3.1e, 2e, 3e). The nitrate, phosphate, and silicate concentrations were recovered–2-7 days after the storm passed.
The observed changes in chemical variables after TC were considered due to the effects of cyclone-induced mixing in offshore areas [4]. In the surface layer of the southern coast of Sawu and Rote Islands, nutrient concentration increased slightly from August 4 to 6, mainly because of vertical mixing or
upwelling events resulting from the strong wind effects. However, the influence of TC on the wind mixing process was attenuated quickly in the study area. At that point, the tropical cyclone had an opportunity to play a fundamental role in the distribution and variation of nutrients.

3.3 Change of environment condition after cyclone supporting ecosystem sustainability
In terms of upwelling phenomena that mainly cause nutrient enrichment and increasing primary production, it could be one of the important studies related to fish stock abundance and its sustainability. Moreover, the study area includes the vital spawning ground of SBT, which spawns throughout the year, with one of the peak activities in October [7]. This reproductive activity may correlate with the annual upwelling event from June to October on the southern coast of Bali and Nusa Tenggara waters, Indonesia [6]. This event was associated with the southeast monsoon cycle, and the upwelling strength was controlled remotely by the ENSO and IOD phenomena [14].

A unique cyclone TC Seroja that awakens near the equator in April in the area was also causing an upwelling event (outside the annual upwelling period). Vertical mixing generated by TC mainly causes nutrient enrichment. Therefore, this phenomenon can be considered to support food security and ecosystem sustainability.

4. Conclusion
The present study has improved the understanding of the influence of tropical cyclones on the marine environment, specifically in the southeastern Indian Ocean. The study results show the alteration of SST (nutrients concentration) induced by the TC Seroja, which decreased (increased) just after the storm passed the region. The changes were recovered between 2 and 7 days after the cyclone. It was essential regarding ecosystem sustainability and food security in the area, considering that the site is vital for commercial fish spawning grounds. However, the relationship between environmental factors and fish stock abundance is expected to be complex.

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