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UPWELLING INTENSITY DURING INDIAN OCEAN DIPOLE PERIOD IN SOUTHERN WATERS OF JAVA

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Abstract. In recent years, the prevalence of IOD has been increasing, leading to widespread and severe consequences. It is imperative to closely monitor this phenomenon in order to comprehend the ecological repercussions and their subsequent outcomes. The objective of this investigation is to examine the occurrence of upwelling in the southern Java waters under neutral conditions and to evaluate potential variations in its intensity during the Indian Ocean Dipole (IOD) season. The research was conducted in the southern waters of Java during the pronounced IOD period from 2016 to 2023. Data were obtained from the Copernicus Marine website, encompassing wind, current, temperature, salinity, and chlorophyll measurements for the eastern season. Subsequent data processing was performed using ArcGIS, ODV, and descriptive statistical methods. The results indicated that during positive IOD events, upwelling in the study area exhibited increased intensity, characterized by reduced surface temperature values, accompanied by elevated salinity and surface chlorophyll concentrations, in comparison to neutral periods. Conversely, during negative IOD events, upwelling demonstrated diminished intensity, as evidenced by higher surface temperatures and comparatively low surface salinity and chlorophyll levels. The vertical distribution of temperature and salinity further corroborated the ascent of subsurface water masses.

1. Introduction

A crucial oceanic process known as upwelling takes place in marine environments, particularly in coastal waters. It occurs when deeper layers of seawater rise to the surface, carrying essential nutrients for primary productivity. In the southern waters of Java, upwelling is one of the main factors that influence the marine ecosystem and fisheries. The waters of southern Java within WPP-NRI 573 continue to harbor viable fishery resources. Additionally, these waters exemplify the unique conditions of fisheries resources that necessitate specialized management approaches (Nurani et al., 2007; Kurniawan, 2019). Meteorological and oceanographic factors make the area located between the continents of Asia and Australia and the Pacific and Indian Oceans intensely experienced, as well as becoming a region that is one of the most affected by climatic events between the two continents and oceans, including the Indian Ocean Dipole (IOD). The interaction between the Asia-Australia Ocean and the Pacific-Indian Ocean significantly influences the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). This relationship is characterized by complex interactions that modulate climate variability across the region (Andrian, *et al*., 2024; Pillai *et al.*, 2021). Climate change trends in Indonesia are causing diverse

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effects across the country. The southern regions are experiencing decreased rainfall and shorter wet seasons, while the northern areas are seeing an increase in precipitation. These alterations in rainfall patterns are leading to shifts in both the onset and duration of the rainy season. (Julismin, 2013).

Such conditions show that the effects of climate, such as those in marine fisheries, are no less important than technical management issues. The catch of cakalang fish in the southern waters of West Java, for example, fluctuates seasonally. Research by Rahman *et al*. (2019) found that the highest catch (325.77 tons) was obtained during the eastern season (2015) when the optimal temperature was 28.00-28.30 °C and chlorophyll-a was optimal 0.20-0.25 mg/m^3. On the other hand, the lowest catch (15.81 tons) occurred during the western season (2016) when the optimal temperature was 27.00-29.00 °C with chlorophyll-a values that were not optimal at 0.00-0.20 mg/m^3.

The IOD is a climate phenomenon that influences weather patterns and ocean circulation in the Indian Ocean region, including the waters around Indonesia. This event is characterized by a temperature differential in sea surface temperatures between the western and eastern sectors of the Indian Ocean. Such temperature variations can lead to alterations in wind patterns and oceanic currents.. Fluctuations in the strength of upwelling in the waters south of Java are frequently linked to the IOD period. These changes have cascading effects on the marine ecosystem, influencing both the distribution of fish and fishing operations in the areas. Indonesia's geographical location, which borders the center of ENSO occurrence in the Pacific Ocean and IOD in the Indian Ocean, makes the Indonesian region highly influenced by both of these climatic phenomena.

The impacts of global climate change are increasingly being felt, including in intertidal ecosystems such as ENSO and IOD, which are becoming more intense. The effects are widespread, including on marine and coastal areas in many regions, such as the waters off southern Java, necessitating a better and more predictive understanding. Climate conditions will impact marine activities, fishing catches, and upwelling in Indonesian waters, including in the waters off southern Java. Off the southern coast of Java, upwelling occurs during the eastern season. Therefore, studying the intensity of upwelling during the IOD period in the waters off southern Java is crucial to understanding the impact of this phenomenon on marine ecosystems and fisheries resources in the area. This study aims to monitor the existence of upwelling in the waters off southern Java during neutral conditions and changes in its intensity during the IOD period. As a result, it is hoped that the results of this study will contribute to the management of fisheries resources and environmental conservation in the waters off southern Java.

2. Research Methods

Research was conducted in the southern waters of Java located at 5–10˚LS and 106–115˚BT, which is divided into three provincial zones (East Java, Central Java and West Java), as depicted in Figure 1. The data used in the study were obtained from the Copernicus website and comprised wind, current, temperature, salinity, and chlorophyll-a in three IOD phases: neutral (June 2017 and June 2018), positive (August 2019 and June 2020) and negative (July 2016 and July 2022). The data were then processed using ArcGIS 10.8 and ODV 5.7.1 to obtain maps of the distribution of each parameter. Upwelling was examined by visually assessing the presence of Ekman transport, which results from the interaction between currents and winds. This phenomenon influences the surface distribution of temperature, salinity, and chlorophyll-a. To complement this analysis, the vertical profiles of temperature and salinity were also investigated.

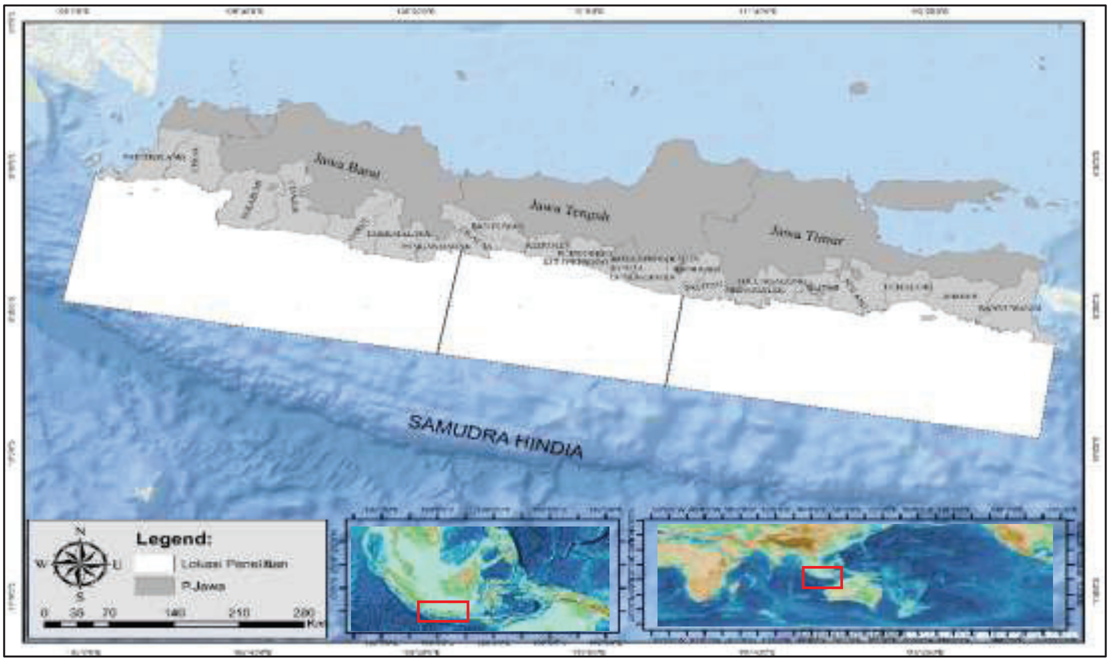

Figure 1. The research location in the southern waters of Java is grouped into three provincial zones: East Java, Central Java and West Java.

3. Result and Discussion

3.1. Ekman Transport

An analysis of surface wind patterns over the southern Java waters during three distinct periods (neutral, positive IOD, and negative IOD - abbreviated as N, pIOD, and nIOD) reveals that southeasterly winds dominate during the eastern season (June, July, and August). The wind speeds are typically highest offshore, reaching approximately 6-7 m/s, while coastal areas experience comparatively lower wind velocities (as shown in Figure 2).

The distribution of surface currents during the N and IOD phases varies in the direction of the wind. The current that dominates the offshore waters is the southwesterly current (as shown in Figure 3). This condition reflects the influence of the upwelling-wind circulation caused by the Coriolis force. In the Southern Hemisphere, the Coriolis effect causes fluids to be diverted in a counterclockwise direction, contrary to the movement of a clock's hands (Natalie *et al.*, 2023; Srinidhi *et al.*, 2019). In the coastal waters, currents are generally deflected away from the shore towards the east. This condition results in the Ekman transport due to the coupling of wind-current, which has the potential to produce upwelling. The existence of the upward movement of subsurface water is indicated by the decrease in sea surface temperature (SST), accompanied by an increase in surface salinity and chlorophyll-a (SSS and SSC-a).

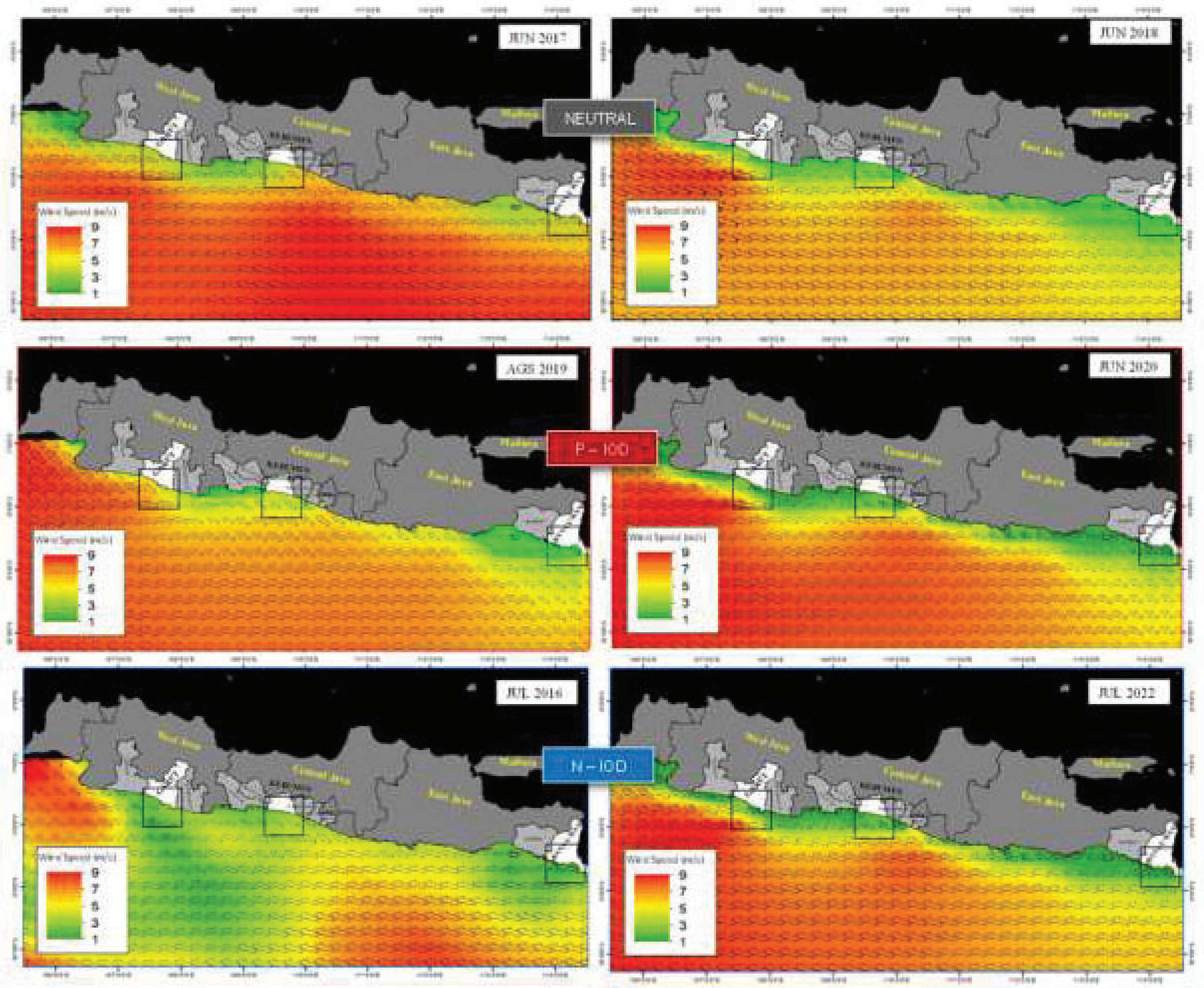

Figure 2. The distribution of surface winds in the southern waters of Java shows the dominance of southeast winds during the eastern season. In general, offshore winds are stronger than the winds in coastal waters.

Strong Ekman transport in South Java waters is influenced by seasonal winds and currents (Atmadipoera *et al*., 2020; Ratnawati *et al*., 2016; Siswanto, 2010). Coastal upwelling processes along Java's southern shoreline are influenced by the interaction between southeasterly winds and seasonal ocean currents. This combination generates offshore Ekman transport, contributing to the upwelling dynamics in the region. (Wirastriya, 2020). In addition to impacting the intensity of Ekman pumping, this wind-current coupling also impacts variations in sea surface temperature and chlorophyll-a levels. Changes in chlorophyll-a levels occur through intraseasonal flow variations that impact the exchange of nutrient-rich water (Schept, 2022; Xu, *et al*., 2018).

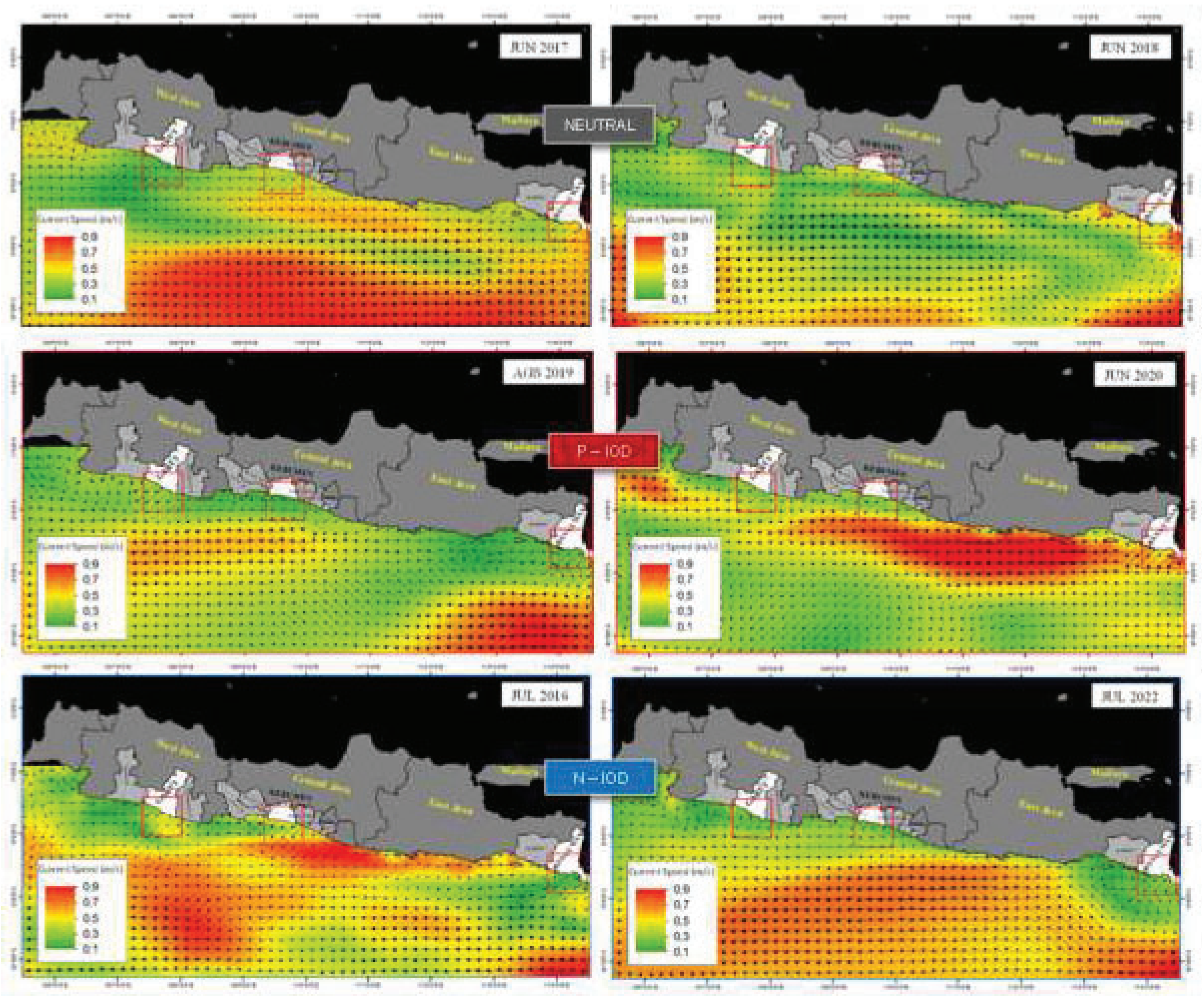

Figure 3. During the eastern season, the N, pIOD, and nIOD phases in Java's southern waters are characterized by predominant westerly currents offshore. In contrast, coastal waters exhibit slower-moving currents that typically deflect southwestward. This current movement causes surface water to be pulled away from coastal areas, creating a vacuum that is subsequently filled by subsurface water masses.

3.2 Distribution of Sea Surface Temperature (SST)

The SST during phase Nl, pIOD, and nIOD in coastal waters of Garut, Kebumen, and Banyuwangi, as shown in Figure 4, confirms a decrease in SST at the three locations during pIOD. During pIOD, with the exception of Kebumen, coastal waters in southern Java experience strong upwelling with a range of 23–24°C. SST drops sharply, approximately 3.00–4.00 °C during pIOD. The SST during the neutral phase and nIOD is similar, with respective ranges of 26.00–28.20 °C and 26.60–27.40 °C. The Garut coast shows high SST during the neutral phase (28.00–28.20 °C), while Banyuwangi shows high SST during nIOD (26.60–27.40 °C).

The difference in temperature during the neutral phase and IOD is further emphasized in Figure 5. The average temperature during N, pIOD, and nIOD is successively 27.17 °C, 24.08 °C, and 27.00 °C. The temperature difference between N-pIOD ranges from 0.80–5.00 °C, with an average of 3.09 °C; whereas the average difference between N-nIOD is 0.17 °C, with a temperature range of 0.00–1.20 °C. This indicates the significance of SST changes in southern Java during pIOD compared to nIOD, and it also confirms that nIOD does not significantly alter the SST characteristics of the southern Java coast.

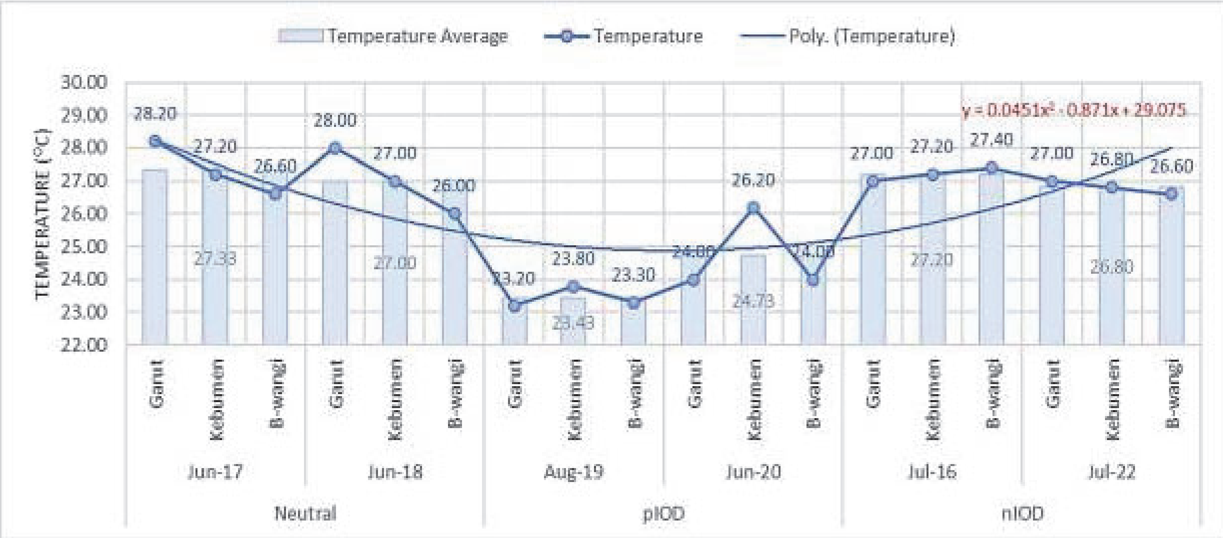

Figure 4. SST fluctuations that emphasize the decrease of SST during pIOD in three loci and the relative equality of SST during neutral phase and nIOD.

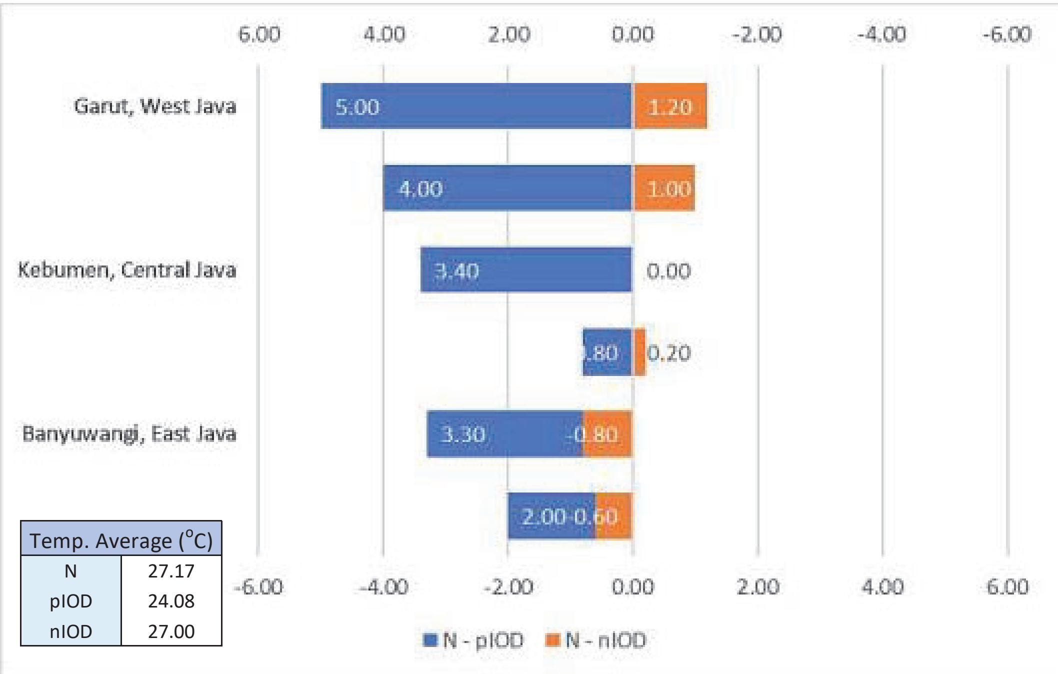

Figure 5. The temperature difference in N compared to pIOD and nIOD which shows the relatively high temperature of N-pIOD.

The small relative SST (indicating upwelling of subsurface water) is depicted in Figure 6. During the research period, such pockets were frequently found at the study locations, namely Garut in West Java, Kebumen in Central Java, and Banyuwangi in East Java. The zone with small SST variations was not constant, but varied and was not far from the three initial locations. For example, Kebumen's relatively high SST was recorded in June 2020 when pIOD was present (Figure 6-pIOD), while SST at the three locations was only ~23.00–24.00 °C. Interestingly, the small SST pocket shifted to the east, specifically to the waters off Gunung Kidul (Yogyakarta). In phase N, the waters off Garut had similar temperatures to those of the relatively high sea surface temperatures (~29 °C) offshore. Conversely, a cold temperature pocket was found along the coasts of Kebumen and Banyuwangi (~26 °C). This

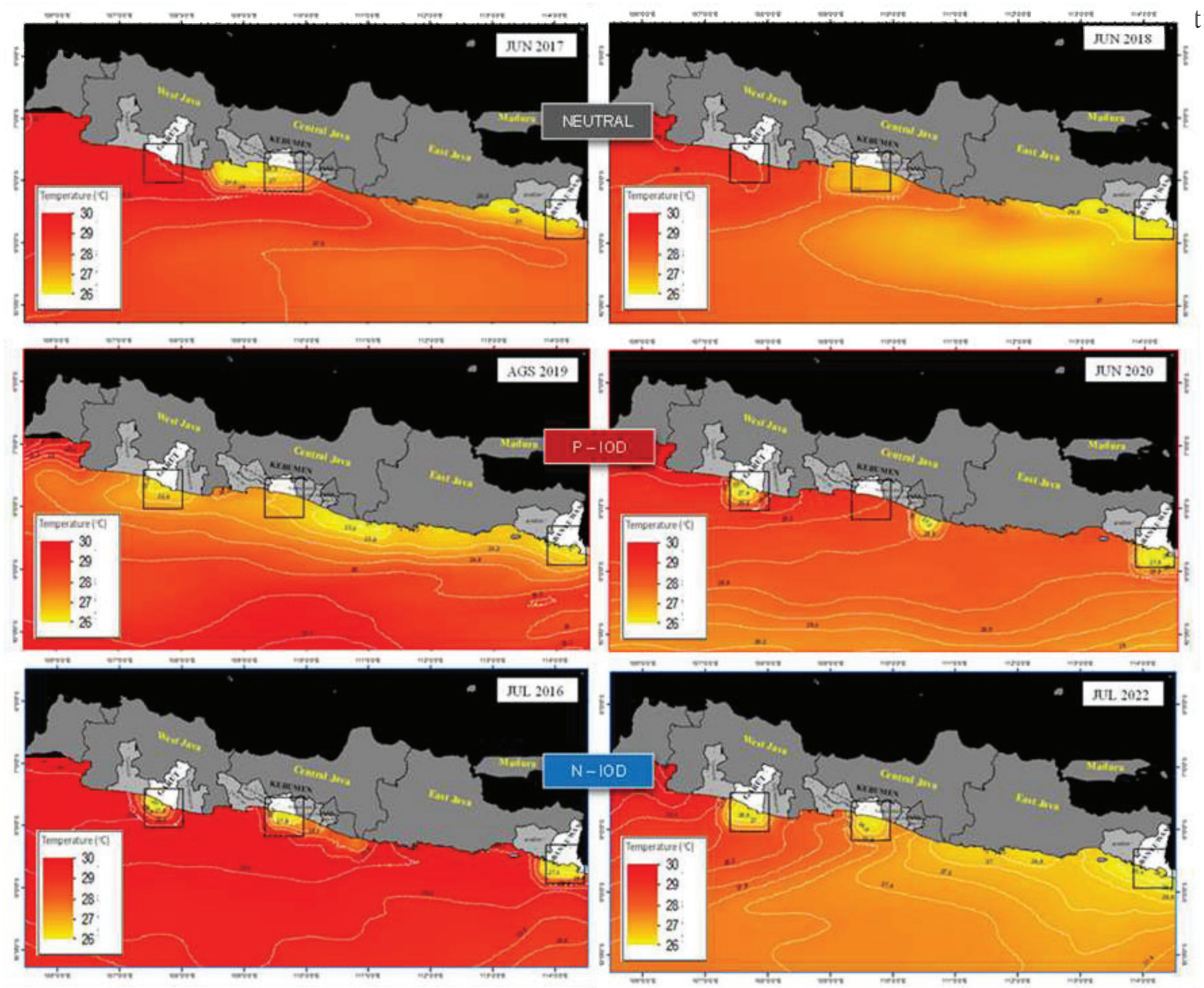

Figure 6. The presence of upwelling in the southern Java waters is evident from SST patterns. Strong upwelling indicators are primarily observed in the coastal areas of Garut, Kebumen, and Banyuwangi. Over time, the upwelling zone has undergone shifts and movements within the vicinity of these three locations.

3.3 Distribution of Sea Surface Salinity (SSS)

The distribution of surface seawater salinity (SSS) exhibits an increase during the Indian Ocean Dipole (IOD) event compared to its neutral phase. The change in the climatic condition of the Eastern Indian Ocean during the positive IOD (nIOD) does not significantly alter the characteristics of the SSS in southern Java compared to when the ocean is cooler than usual. The SSS ranges at the three loci during the IOD event varied between 34.20 PSU (Garut, June 2020) and 34.60 PSU (Banyuwangi, August 2019). Meanwhile, the SSS range during N and nIOD, respectively, was between 33.80 PSU (Garut, June 2017) and 34.20 PSU (Kebumen and Banyuwangi, June 2018) and 34.00 PSU (Kebumen and Banyuwangi, July 2022) to 34.20 PSU (Kebumen and Banyuwangi, July 2016), see Figure 7.

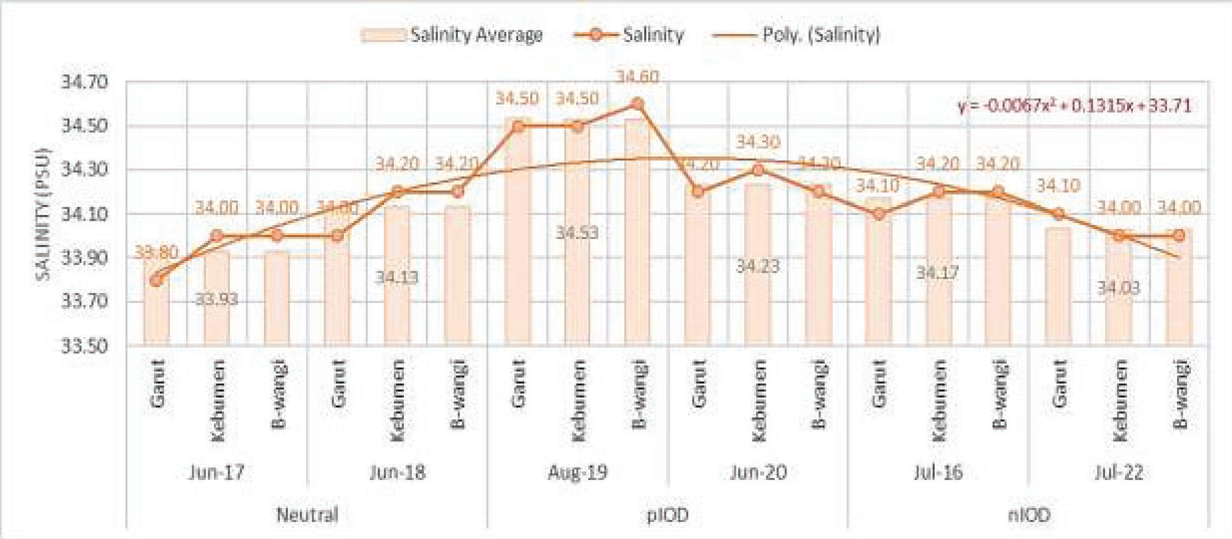

Figure 7. SSS fluctuations in Garut, Kebumen and Banyuwangi waters that show an increase in SSS during the pIOD compared to the N and nIOD.

Figure 8 illustrates how positive and negative IOD events, resulting from climate change, affect the neutrality of waters in the southern Java Sea.. A comparison between the two shows that the highest range of N-pIOD reaches 0.70 PSU in the waters off Garut, while the lowest 0.00 PSU occurs in Banyuwangi. On the other hand, the N-nIOD range reaches a maximum of 0.30 PSU in Garut and a minimum of 0.10 PSU in the same waters. This indicates that during an IOD event, there is an increase in salinity compared to the neutral phase. The stronger increase in SPL in the southern Java Sea occurs during pIOD (0.35 PSU) compared to nIOD (0.07 PSU).

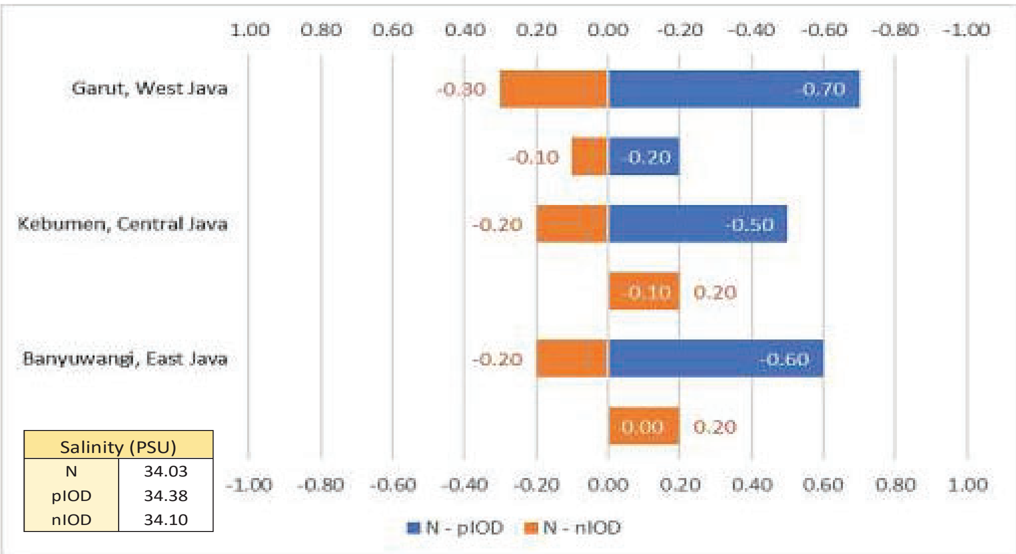

Figure 8. Salinity differences during the pIOD and nIOD compared to the neutral phase showing a more significant increase in SSS during the pIOD.

The spatial distribution of SSS displayed in Figure 9 shows the distribution of high SSS patches. During nIOD, particularly in July 2016, high SPL patches were found to be scattered across three loci. The increase in SSS in coastal waters during pIOD was marked by an increased isohaline. SSS in the Garut waters appeared more spotty than in the waters of Kebumen and Banyuwangi, indicating the strength of the subsurface water mass increase in the Garut waters. During the neutral phase, seawater along the southern coast of Java had relatively similar SSS values (~34.00 PSU). The waters of Garut also showed relatively lower SSS compared to the southern Java waters in general.

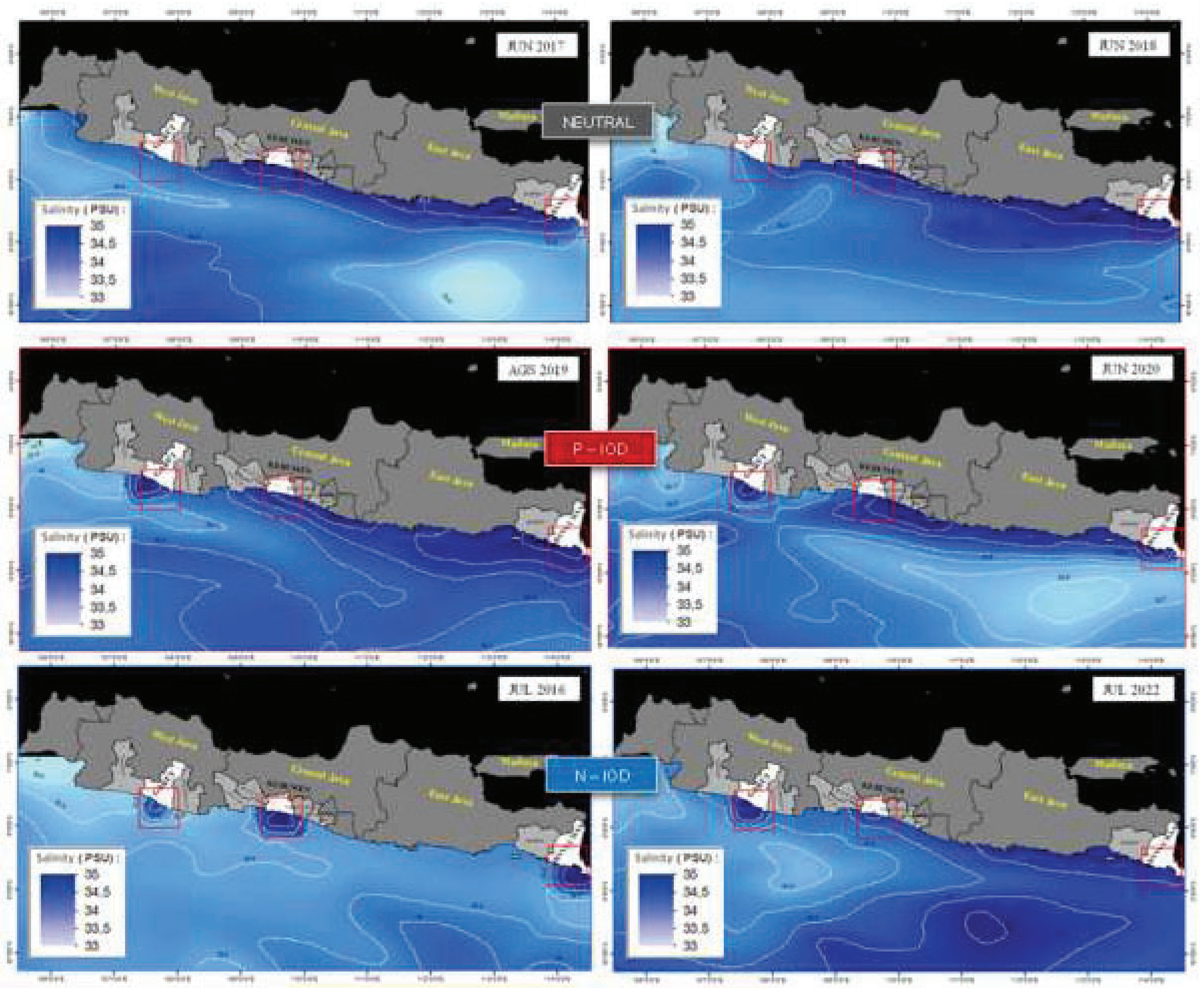

Figure 9. Spatial distribution of SSS in southern Java waters showing relatively high SSS during the pIOD compared to the nIOD. The low SSS during the nIOD confirms the wet period when the eastern Indian Ocean waters are warmed compared to neutral conditions.

3.4 Distribution of Sea Surface Chlorofil-a (SSC-a)

The temporal fluctuation of SSC-a, as depicted in Figure 10, resembles the temporal fluctuation of SPL marked by an increase in SSC-a during pIOD with a peak of 1.80 mg/m^3 in Banyuwangi waters (August 2019). The lowest SSC-a dominated nIOD, particularly in July 2016 with values of 0.12–0.14 mg/m^3 in Garut, Kebumen, and Banyuwangi waters. Although still relatively low, SSC-a in July 2022 at all three locations increased to 0.30–0.40 kg/m^3. The neutral water phase in Garut also had a low SSC-a of 0.12 mg/m^3 in June 2017. Comparing SSC-a during N with pIOD and nIOD shows the high SSC-a during pIOD, with a range of 0.1–1.28 mg/m^3 compared to the neutral phase. Meanwhile, with an average of 0.25 mg/m^3, nIOD conditions lowered SSC-a to 0.71–1.00 mg/m^3 compared to the neutral phase (Figure 11).

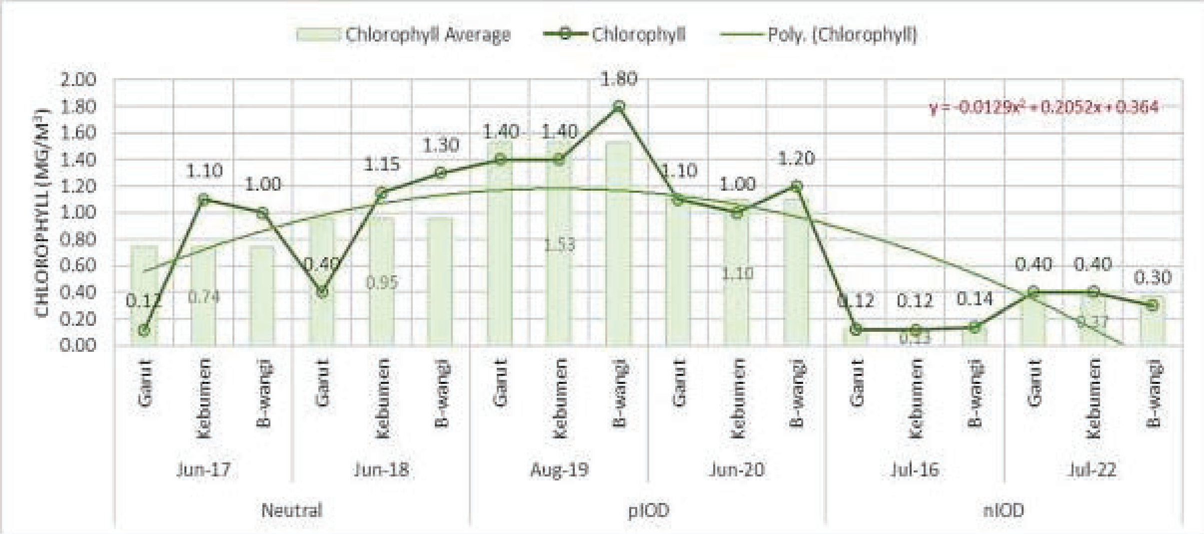

Figure 10. SSC-a fluctuations showing increased SSC-a during pIOD compared to N and nIOD in Garut, Kebumen and Banyuwangi waters.

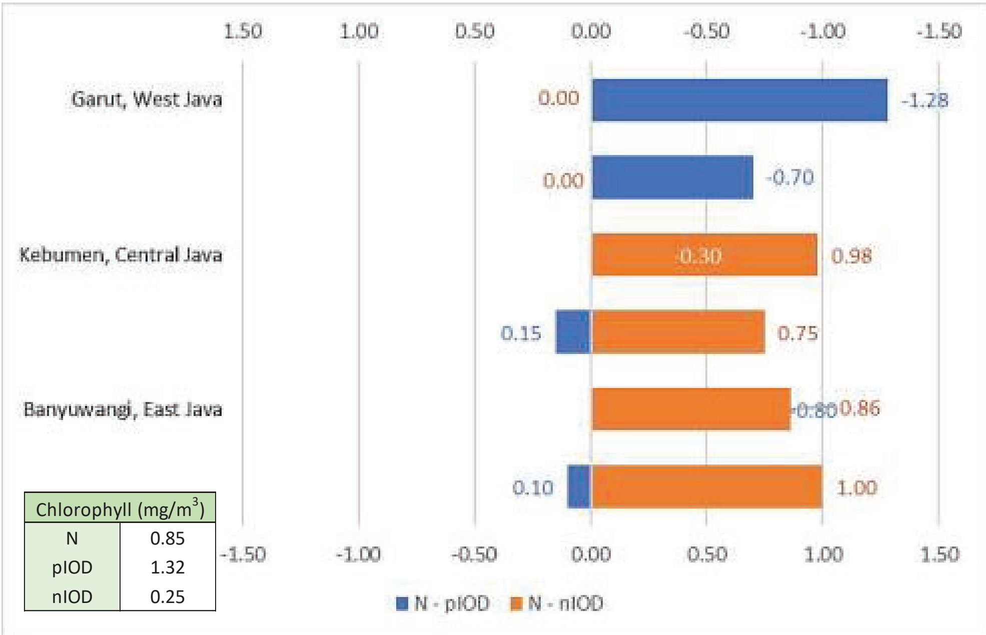

Figure 11. The difference in neutral phase SSC-a with pIOD and nIOD shows the relatively balanced influence of pIOD and nIOD. On average, SSC-a during pIOD increased by 0.47 mg/m^3, while during nIOD it decreased by 0.60 mg/m^3.

The distribution of SSC-a during the neutral phase, as shown in Figure 12, indicates that the seawater in Kebumen and Banyuwangi has a higher SSC-a than that of the oceanic water. However, the same condition was not found in the Garut coastal area. In the West Java location, the distribution of SSC-a is similar to SST, which has similarity with oceanic water in the western and southern areas. During the IOD period, whether positive or negative, the three locations showed high pockets of SSC-a that stood out compared to the oceanic water. Overall, SSC-a increases during pIOD and decreases during nIOD.

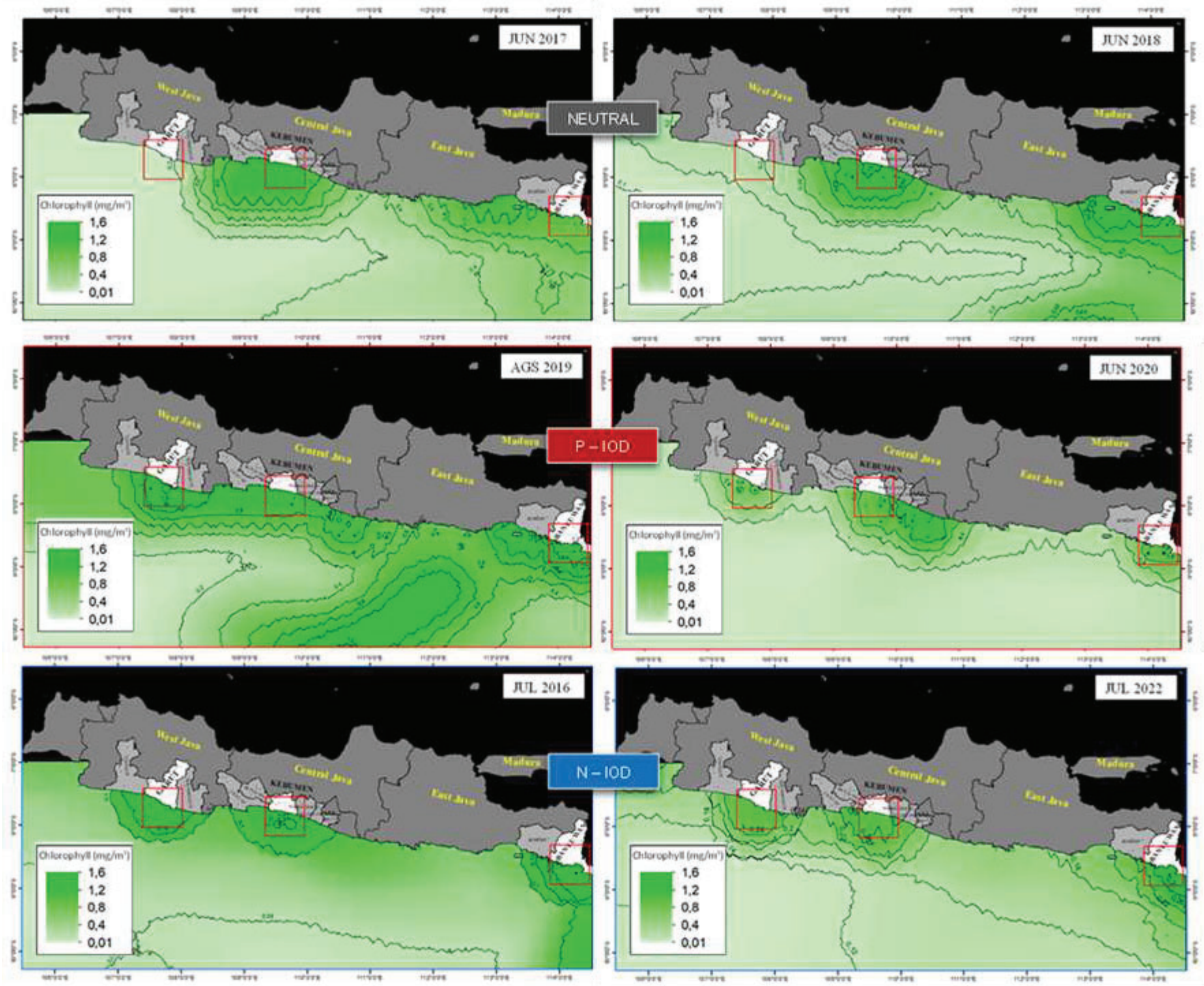

Figure 12. The distribution of SSC-a in the south coast of Java during the neutral and IOD phases shows the relatively high SSC-a content of coastal waters compared to oceanic waters. Compared to the neutral phase, the SSC-a contours during the pIOD show an increase, while those during the nIOD decrease. The SSC-a pockets at the three loci are still prominent, except in Garut during the neutral phase.

3.5 Vertical Profile of Temperature dan Salinity

The subsurface water mass rise to the surface supports the occurrence of upwelling at the study site, represented by temperature and salinity during the pIOD (Figure 13), which has a greater impact in changing oceanographic characteristics (temperature, salinity, and chlorophyll). The vertical profile of temperature (VPT) indicates the presence of isotherms rising and concentrating at three loci: Garut, Kebumen, and Banyuwangi (Figure 13 left). VPT also shows higher isotherm elevation in Gunung Kidul compared to Kebumen, as indicated by the SST distribution shown in Figure 6. The more intense rise in water mass in August 2019, with an isotherm of 24 °C at the surface, compared to June 2020, with an isotherm of 4 °C (Figure 13), indicates that the warmer water mass originated from a deeper depth. In August 2019, the isotherm of 24 °C shows a more intense rise to the surface, with colder water, compared to the isotherm of 28 °C. The vertical profile of salinity (VPS) during the same period also shows a subsurface water mass rise. The isohaline that reaches the surface in August 2019 reaches 34.6 PSU, which is 0.6 PSU higher than in June 2020.

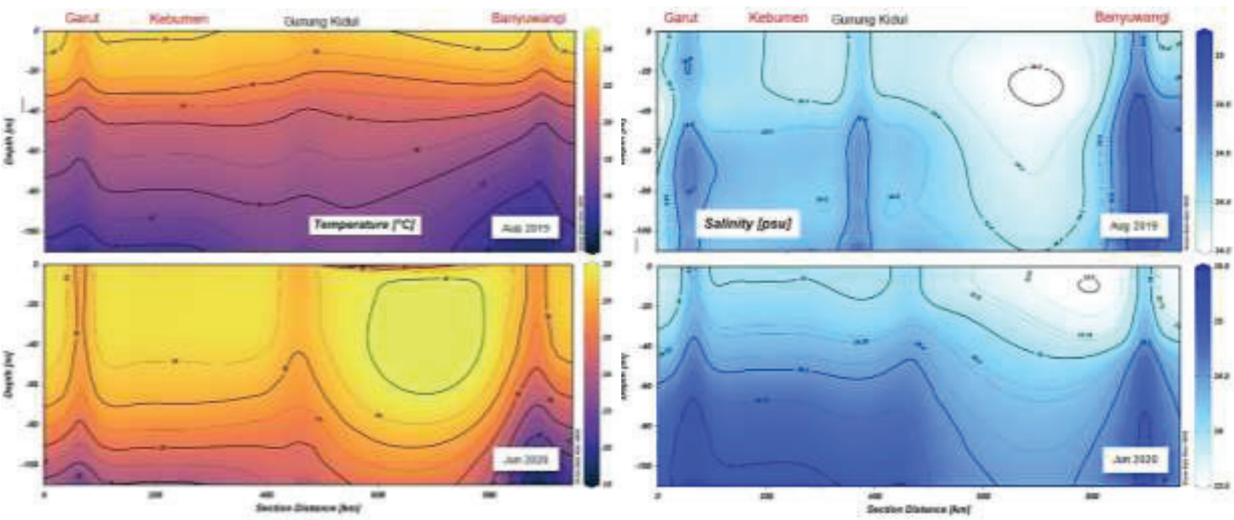

Figure 13. VPT (left) and VPS (right) showing a subsurface water mass increase. Isotherms and isohalines reaching the surface in August 2019 were cooler and saltier than those in June 2020.

Increased upwelling intensity during pIOD is characterized by a decrease in SST and increases in SSS) and SSC-a (Herlambang and Iskandar, 2023; Clair, 2022; Horii et al., 2022). The movement of cold water masses at three research loci indicates thermocline uplift which, as stated by Horii et al. (2018), signifies the occurrence of upwelling. Conversely, nIOD reduces upwelling intensity in the southern waters of Java, evidenced by increased SST and decreased SSC-a (Undap et al., 2023; Koropitan et al., 2021). The research findings align with those of Atmadipoera et al. (2020), who observed that pIOD enhances upwelling intensity, while nIOD attenuates it. Furthermore, Rahman et al. (2020) assert that IOD exerts a more significant positive impact on coastal upwelling intensity in the southern waters of Java compared to ENSO. Additionally, Wang et al. (2021) demonstrate the influence of the Indonesian Throughflow on upwelling during pIOD (2019) and nIOD (2016) events.

4. Conclusion

The southern waters of Java experience upwelling during the eastern season. The prevailing wind-sea currents that generally move southwest result in the production of an Ekman transport that carries surface coastal water away from the coast, resulting in a void of surface water near the coast. This surface water void is replaced by upwelling water from below the surface, resulting in a colder temperature characteristic, as well as a larger surface temperature, salinity, and chlorophyll in comparison to the surrounding waters. During the neutral period without the influence of IOD, the average temperature, salinity, and chlorophyll of the waters in southern Java were 27.17 °C, 34.03, and 0.85 mg/m^3, respectively. The upwelling phenomenon continues throughout the eastern season with varying intensities. The waters of Garut are included in the area with weak upwelling during the neutral phase.

The impact of pIOD on southern Javan waters is more pronounced than that of nIOD. During the pIOD phase, which corresponds to the dry season and is characterized by cooling of the Indian Ocean surface, the average temperature dropped by 3.09 °C. In contrast, during the nIOD phase, associated with the wet season and warming of the Indian Ocean's surface layer, the average temperature only decreased by 0.17 ^{o}C when compared to the neutral phase. On average, the SST increased by 0.35 PSU during pIOD and only by 0.07 PSU during nIOD. The SSC-a decreased by 0.60 mg/m^3 during nIOD and increased by 0.47 mg/m^3 during pIOD compared to the neutral phase.

Upwelling on the southern waters of Java during the eastern season does not always occur in the same area. The location of the research shows a shift in the strong upwelling zone towards the east, from the Kebumen waters to Gunung Kidul, Yogyakarta in Central Java, as well as a shift towards the west in East Java, from Banyuwangi to Lumajang.

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