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Impacts of La Niña on Sea Surface Temperature, Chlorophyll-a, and Fishery Productivity in Northern East Java Ocean

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Abstract
The La Nina phenomenon occurs when the sea surface temperature in the Northeast Pacific Ocean becomes colder. Meanwhile, temperatures in the Western Pacific Ocean are warmer than usual. Such conditions affect the oceanographic conditions of Indonesia's waters, including the Northern Waters of East Java. Therefore, it is necessary to conduct research aimed at analyzing the impact of the La Nina phenomenon on the fertility of the Northern Waters of East Java, through observations of sea surface temperature (SST) distribution, chlorophyll-a concentration, and fish catch data. SST data and chlorophyll-a concentration were obtained from Aqua-MODIS satellite images and analyzed using quantitative methods. Meanwhile, fish catch data were obtained from seven fishing ports on the North Coast of East Java. The results showed that the SST cycle in East Munson was not affected by the La Nina phenomenon. However, La Nina affects the ever-increasing SST anomaly value. The SST cycle in West Munson decreased in the La Niña period. Chlorophyll-a anomaly values also decreased during the La Nina period, especially from October 2017 to April 2018. Chlorophyll-a anomaly values tend to increase in the La Nina period from August 2020 to December 2022. This is influenced by the IOD (-) period. There was a time lag in the effect of SST and chlorophyll-a on fish catches. During La Nina, fertility rates in the Northern Waters of East Java tend to be low, marked by warming sea surface temperatures, uneven distribution of chlorophyll-a, and reduced fish catches. Such conditions can be taken into consideration in the planning of mitigation measures for the impacts of La Niña in the maritime and fisheries sectors in the upcoming period.

1. Introduction

The marine area along the northern coast of East Java holds strategic ecological and socio-economic significance. It forms an integral part of Indonesia’s coastal and marine ecosystem, serving as a vital zone for fisheries and local livelihoods. Due to its ecological importance, maintaining the sustainability of marine fertility in this region must be a principal consideration in environmental management practices. However, large-scale climatic anomalies, particularly the La Niña phenomenon, can exert considerable influence on marine fertility dynamics. The occurrence of La Niña introduces significant shifts in atmospheric and oceanographic parameters, thus warranting in-depth investigation into its potential impacts on marine productivity in the waters of northern East Java.

A key challenge in addressing this issue lies in the limited availability of empirical data and scientific understanding regarding critical oceanographic indicators, such as **Sea Surface Temperature (SST)** and **chlorophyll-a concentration**. These two variables are widely recognized as proxies for aquatic productivity and play essential roles in shaping the spatial and temporal variability of fishery resources. Numerous studies, including those by Sidik et al. [1], Syetiawan [2], and Apriliani et al. [3], have consistently identified SST and chlorophyll-a as the principal determinants in the identification of productive fishing grounds. This is because SST is a primary factor controlling the thermal regime of marine environments, which directly affects the physiology, distribution, and migratory behavior of fish species [3].

SST can also be used as an indicator to identify upwelling zones—areas where cooler, nutrient-rich waters from deeper layers ascend to the surface, leading to enhanced phytoplankton productivity. According to Kurniawati et al. [4], such upwelling events are typically marked by decreased SST and elevated chlorophyll-a concentrations, thereby promoting higher trophic productivity and increasing fish biomass in the region.

Chlorophyll-a, on the other hand, is a photosynthetic pigment found in phytoplankton and is used extensively to assess primary productivity. The concentration of chlorophyll-a reflects the abundance of phytoplankton in surface waters, which form the base of the marine food web. Elevated chlorophyll-a levels indicate fertile waters, as they support a greater diversity and abundance of marine life. This relationship is further supported by research from Vikri et al. [5] and Apriliani et al. [3], who emphasized the role of chlorophyll-a in identifying productive feeding grounds for pelagic fish species.

The interaction between SST and chlorophyll-a is often characterized by an inverse relationship: higher SSTs generally lead to reduced chlorophyll-a concentrations, and vice versa. However, the influence of these parameters on fish catch is not instantaneous. Andhita et al. [6] found that there is a **time lag of approximately one month** between fluctuations in SST or chlorophyll-a and their measurable impact on fishery yields. This time lag is attributed to the biological response time required for plankton and fish populations to adjust to changing environmental conditions. Moreover, this delay is further influenced by the **trophic level** of fish species, as organisms occupying higher levels in the food chain require longer periods to respond to increases in primary productivity [7], [8].

Phytoplankton, being the foundational component of marine food webs, utilize chlorophyll-a and other pigments to perform photosynthesis—converting sunlight and carbon dioxide into energy. These organisms are crucial not only for sustaining marine biodiversity but also for modulating global biogeochemical cycles, including the carbon cycle. Therefore, measuring chlorophyll-a concentrations provides a useful indicator for assessing the fertility of ocean regions and the broader productivity of marine ecosystems.

To support sustainable fisheries and marine conservation strategies, continuous and comprehensive monitoring of SST and chlorophyll-a is essential. However, the vast expanse of Indonesia’s maritime domain makes direct oceanographic measurements logistically challenging and economically prohibitive. Consequently, **remote sensing technologies**, particularly satellite imagery, have emerged as practical tools for large-scale monitoring of ocean conditions. These tools enable researchers to collect spatially and temporally extensive data on SST and chlorophyll-a distribution, thereby facilitating more informed management decisions. This underscores the importance of assessing the impacts of La Niña events on SST and chlorophyll-a as a means of understanding their downstream effects on marine ecosystems and fishery productivity.

A number of scientific investigations have previously examined the consequences of El Niño-Southern Oscillation (ENSO) events—including La Niña—on various aspects of the atmosphere, hydrosphere, and biosphere. Moura et al. [9], for instance, analyzed climatic parameters such as rainfall, temperature, and evapotranspiration across the Amazon Basin from 2000 to 2016. Their findings revealed that La Niña periods are associated with increased precipitation relative to neutral years, whereas El Niño conditions typically suppress rainfall.

In the oceanographic context, Arsen’yev et al. [10] developed a mathematical model based on mesoscale turbulence theory to investigate current dynamics in the equatorial Pacific during ENSO phases. Their model uncovered a vertically layered current structure, where surface trade winds overlay subsurface and intermediate currents. These patterns undergo significant rearrangements during El Niño and La Niña events, altering the flow structure and mixing dynamics of equatorial waters.

Similarly, Darwin Aramburo et al. [11] studied the spatial and temporal patterns of ocean waves in the Pacific Ocean under different ENSO conditions. They found that, historically, strong wave activity dominated by extratropical cyclones prevailed between 1960 and 1990, particularly during La Niña events. After 1990, the regions of maximum wave heights shifted further into subtropical latitudes, coinciding with intensified southeast trade winds during La Niña phases.

Research by Horikawa et al. [12] explored the variability in sea surface salinity and stable oxygen isotopes (δ18Osw) to assess their use as proxies for reconstructing past ENSO events in the South Pacific Convergence Zone (SPCZ). Their results indicated weak correlations between δ18Osw and salinity in the region, suggesting the need for more granular data during ENSO phases to improve reconstructions of paleoclimate records.

Recent climate patterns also suggest deviations from historical trends. Shi et al. [13] observed that La Niña events occurring between 2020 and 2023 were not preceded by strong El Niño events, contrary to conventional patterns. Instead, these La Niña episodes followed neutral conditions and were driven by anomalous SSTs and wind patterns in the tropics.

Beyond physical parameters, La Niña also influences biological processes. Sánchez-Caballero et al. [14] studied reef fish populations in the southern Gulf of California after the 2010 and 2012 ENSO events. They found that seasonal dynamics and species-specific responses were more pronounced than broader community-level changes, suggesting resilience of coral reef fish communities despite climate variability.

The chemical-biological interplay during La Niña was highlighted in a study by Li et al. [15], who examined concentrations of **dimethyl sulfoniopropionate (DMSPt)**, a compound produced by phytoplankton. Their study found a positive correlation between DMSPt, SST, and chlorophyll-a during the 2021 La Niña period, indicating heightened phytoplankton activity driven by anomalous SST values. Fish distribution patterns are also responsive to ENSO variability. Wang et al. [16] employed gradient forest and generalized additive models to investigate environmental influences on red drum (Paerargyrops edita) abundance in the northern Beibu Gulf. SST, sea surface salinity, and the Niño 3.4 index were found to significantly affect fish presence, underlining the ecological relevance of ENSO-related parameters.

Another notable study by Zhao et al. [17] examined how ENSO phases affect mackerel physiology and mercury bioaccumulation. Sampling during La Niña (2021) and El Niño (2023) years revealed that smaller mackerel had improved physiological conditions during El Niño, while larger specimens exhibited reduced health. Moreover, mercury concentrations spiked during the El Niño period, suggesting enhanced contaminant transfer linked to altered food web dynamics.

Lastly, Khan et al. [18] analyzed SST, dissolved oxygen, nitrate levels, and chlorophyll-a during La Niña from 2020 to 2022, identifying significant SST declines during transitional seasons. Their findings emphasized that La Niña has substantial effects on the productivity of the Eastern Indian Ocean, particularly through its modulation of chlorophyll-a concentrations.

In conclusion, the La Niña phenomenon plays a multifaceted role in shaping marine environmental conditions, particularly in regions such as the northern waters of East Java. Its influence on SST and chlorophyll-a not only affects the primary productivity of the marine ecosystem but also cascades through trophic levels to impact fisheries, species distributions, and even contaminant dynamics. The integration of satellite-based remote sensing with oceanographic and biological models offers promising pathways for future research and policy formulation aimed at safeguarding Indonesia's marine resources.

2. Methodology

Quantitative research with a focus on data collection and processing for the generalization of research objects is implemented in this research. Data processing was carried out on SST, chlorophyll-a, and fish catches in the Northern Waters of East Java.

SST and chlorophyll-a data were downloaded from http://ocelancolor.gsfc.nasa.gov/ with monthly composites. SST and chlorophyll-a data are level 3 data (Level 3 Mapping), which is data obtained from geophysical variables and has been aggregated into defined spatial grid data, in a defined period. The Aqua-MODIS data is then processed using the SeaDAS 8.4.1 application.

Spatial data from satellite imagery were collected over the period 2017–2022 in monthly time series. Meanwhile, fish catch data were grouped into quarterly time series. The La Niña period from 2017 to 2022 was chosen because the La Niña phenomenon has the potential to affect the fertility conditions of the waters. Meanwhile, the sustainability of aquatic fertility must be the focus of environmental management in the waters.

The geometry data processing process is to convert the. NC into .txt form. The data .txt is used for graph analysis. Spatial maps are created with the help of the ArcGIS 10.8 program. The Map of the Northern Waters of East Java is stored in a database directory with the format "*.img".

The data analysis applied is in the form of multiple linear regression, as it only utilizes one dependent variable and two independent variables. The results of the regression analysis include the acquisition of t-statistic, F-statistic, and R^2 values. The t-statistic value will reveal the regression coefficient of each independent variable, individually affecting the dependent variable (Y). Meanwhile, the F-statistic value will indicate the joint effect of the variables. The R^2 value is used to measure how well the regression model can explain the variability of the dependent variable.

3. Results and discussions

3.1 Sea Surface Temperature (SST) Variability

The SST anomaly declined during the El Niño period (September 2018–June 2019) and remained suppressed during the IOD(+) phase (May 2019–December 2020). Conversely, SST anomalies increased significantly during the La Niña event (August 2020–December 2022), with additional warming during the IOD(–) phase (May–December 2022), as illustrated in **Figure 1**. These shifts affirm that SST responds dynamically to ENSO and IOD interactions. According to Moura et al. [9], La Niña redistributes heat from east to west Pacific, often elevating SST in Indonesian waters.

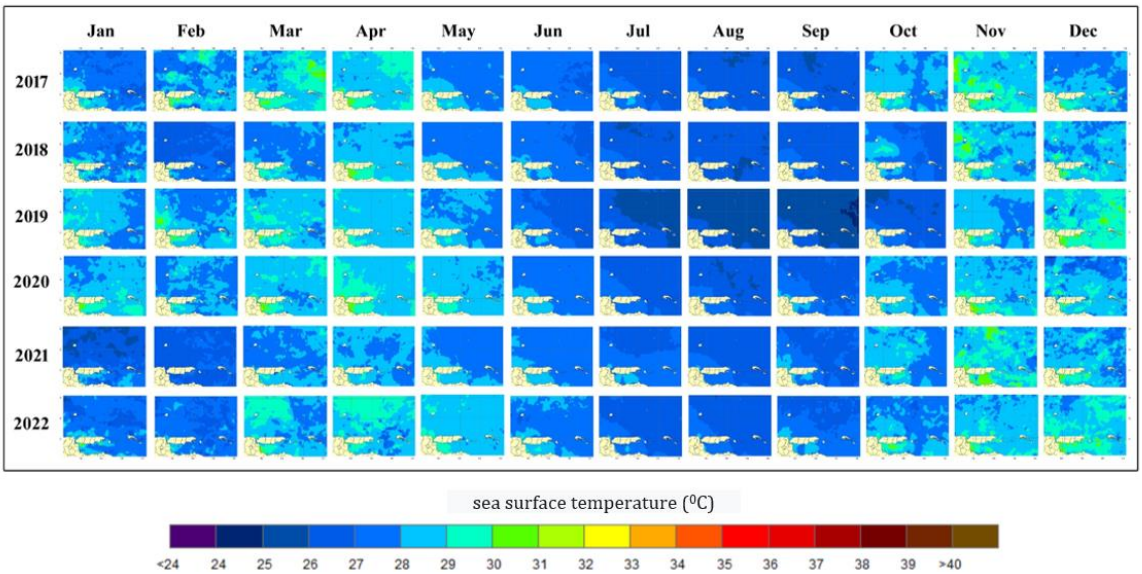

Figure 1. SST Distribution Map 2017 – 2022

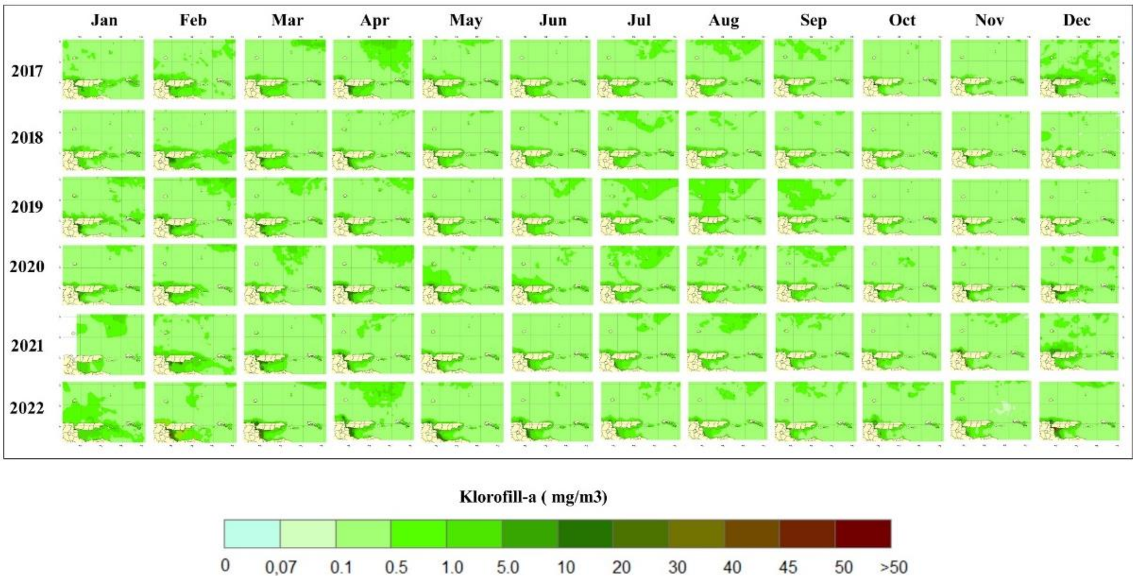

Figure 2. Chlorophyll-a Distribution Map 2017-2022

3.1.1 SST in the Eastern Monsoon

As shown in the SST time series (see **Figure 1**), April marked the annual peak, followed by a decline in August–September, and a rebound in October. During La Niña years (2020–2022), SST anomalies in the Eastern Monsoon rose, particularly when the Dipole Mode Index (DMI) was negative (IOD–). These findings reflect a reinforcing effect between La Niña and IOD– in elevating coastal SST, especially around the monsoonal shift.

3.1.2 SST in the Western Monsoon

In contrast, the Western Monsoon exhibited cooler SST anomalies during La Niña years (2017–2018, 2020–2022), breaking from the seasonal warming trend. These deviations (visible in **Figure 1**) suggest that La Niña suppresses warming, potentially disrupting vertical stratification and delaying upwelling onset. This pattern is consistent with Wingking [8], who observed ENSO-related SST anomalies disrupting tuna migration corridors in Eastern Indonesia.

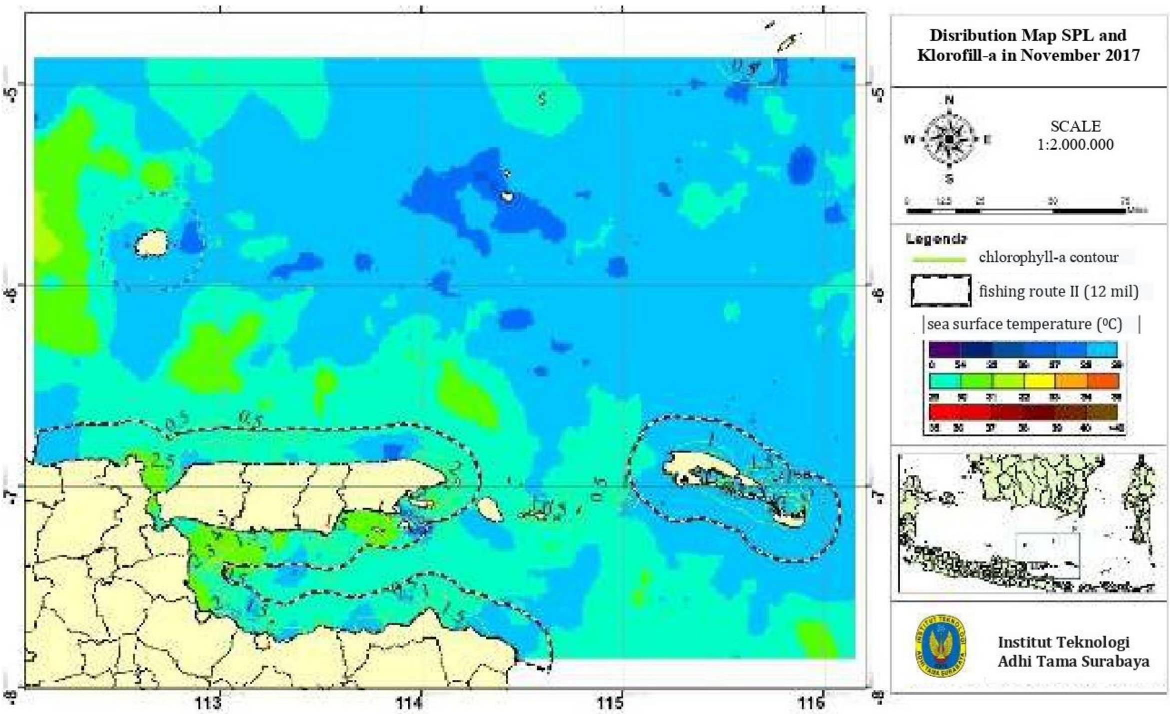

Figure 3. Distribution Map of SST and Chlorophyll-a, November 2017

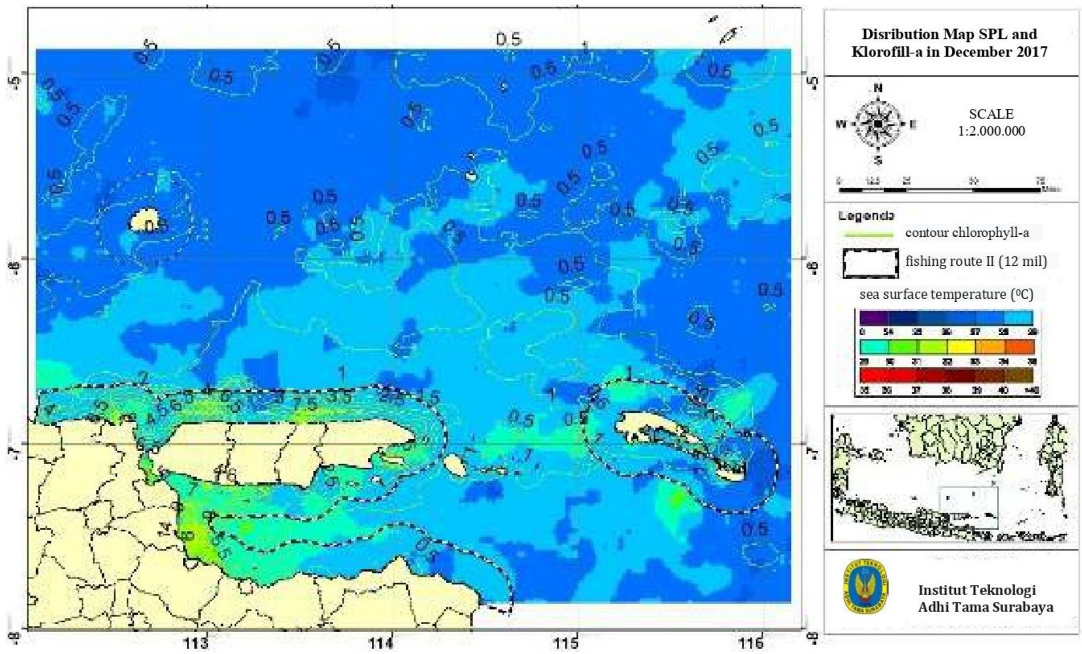

Figure 4. Distribution Map of SST and Chlorophyll-a, December 2017

3.2 Chlorophyll-a Variability

Chlorophyll-a anomalies, as seen in **Figure 2**, dropped during the 2017–2018 La Niña phase, rose through El Niño (2018–2019), and peaked during the IOD(+) phase (2019–2020). During the second La Niña (2020–2022), anomalies fluctuated with an overall increasing trend—particularly under IOD(–) influence. These shifts confirm that chlorophyll-a responds not only to SST but also to nutrient delivery modulated by oceanic currents and wind forcing [3], [4].

3.2.1 Chlorophyll-a in the Eastern Monsoon

Despite a declining average during Eastern Monsoon periods, anomalies in 2018, 2019, and 2021 (highlighted in **Figure 2**) increased—coinciding with major phase transitions in ENSO and IOD. For example, April 2018 marked the tail end of La Niña, and September marked early El Niño onset. The spike in 2021 aligns with La Niña and negative IOD, consistent with chlorophyll-a enhancement due to stronger upwelling, as suggested by Kurniawati et al. [4].

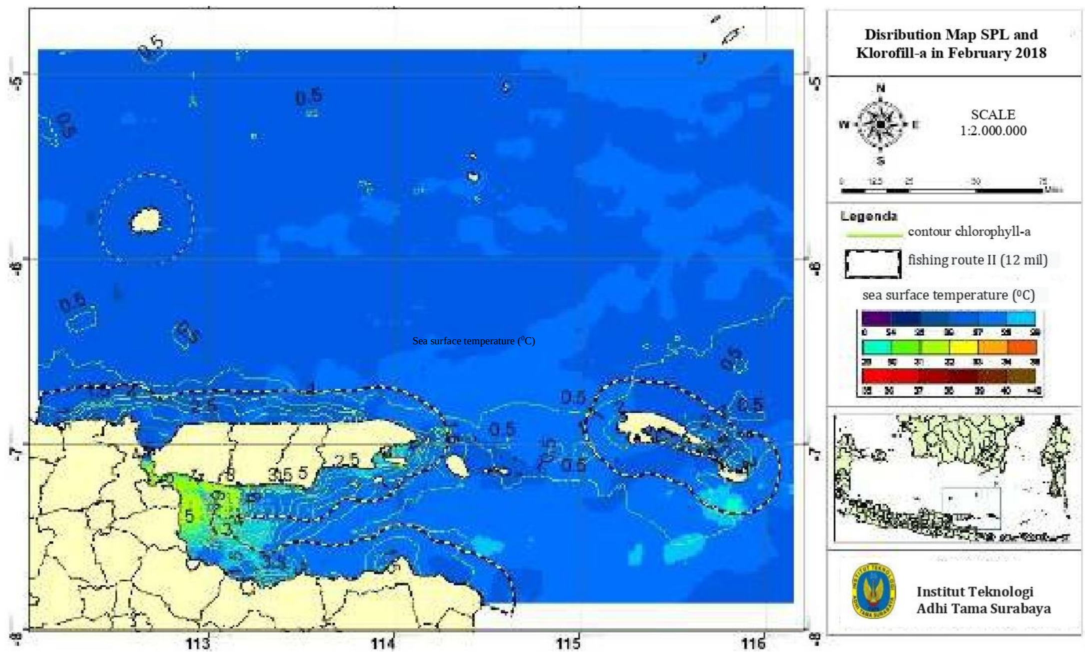

Figure 5. Distribution Map of SST and Chlorophyll-a February 2018

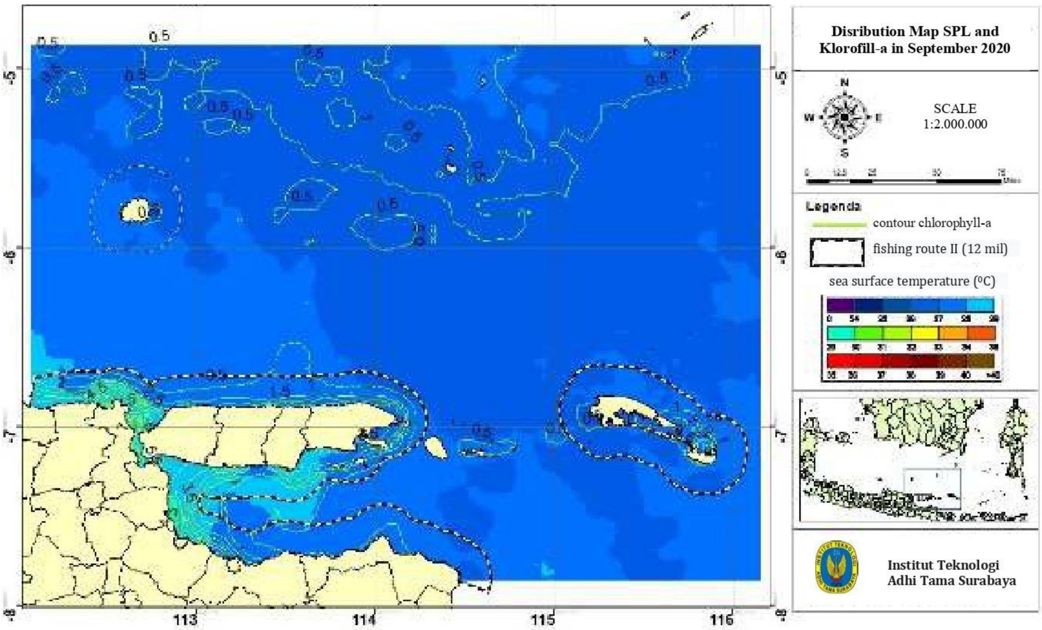

Figure 6. Distribution Map of SST and Chlorophyll-a, September 2020

3.2.2 Chlorophyll-a in the Western Monsoon

Chlorophyll-a during the Western Monsoon was more volatile (see **Figure 2**), with reductions in 2017–2018 and 2020–2021 La Niña periods, yet increases in 2021–2022. These inconsistencies highlight the role of overlapping climate modes and local dynamics. Vikri et al. [5] emphasized how thermal fronts and eddy circulation significantly shape western Indonesian phytoplankton fields, particularly under variable ENSO conditions.

3.3 SST, Chlorophyll-a, and Fish Catch Variability

Figure 2 (chlorophyll-a) and fisheries catch records (not shown) demonstrate that peak fish landings occurred during the El Niño and IOD(+) phases, when SST was lower and chlorophyll-a higher. Conversely, La Niña led to reduced catches despite SST increases. These results support Andhita et al. [6], who found that SST and chlorophyll-a influence catch rates with a 1-month time lag due to food web dynamics. Trophic delays, as explained by Almohdar and Soulisa [7], likely moderated catch responses in this study.

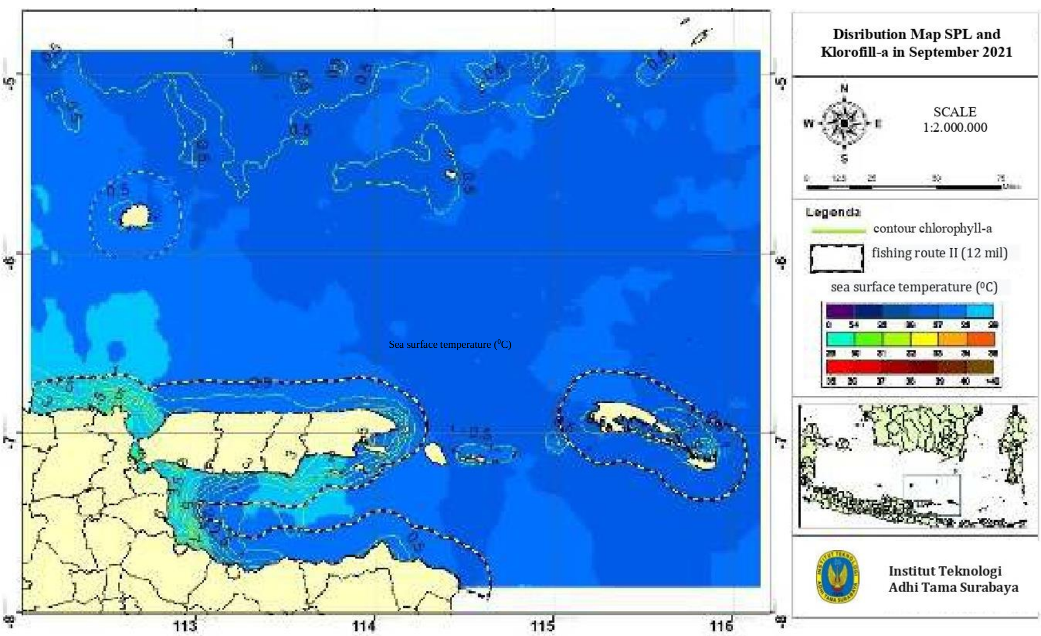

Figure 7. Distribution Map of SST and Chlorophyll-a, September 2021

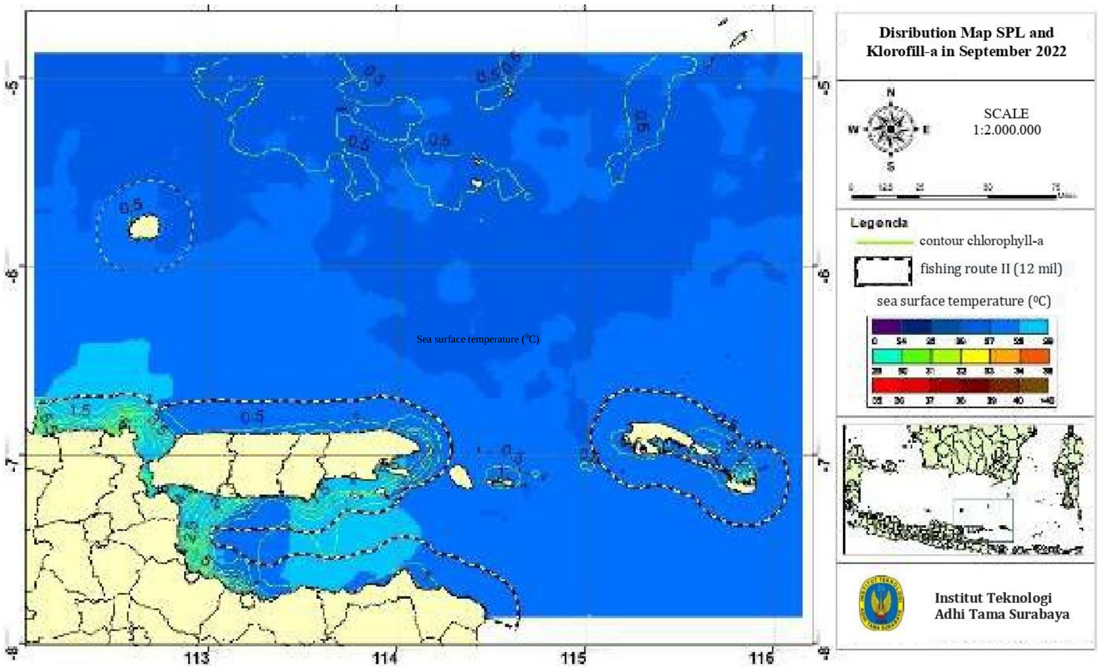

Figure 8. Distribution Map of SST and Chlorophyll-a in September 2022

3.4 Spatial Data Distribution of SST and Chlorophyll-a

Figure-based observations confirm the patterns discussed above. During the 2017–2018 La Niña, **Figure 3** (November 2017) shows coastal waters warmed, while **Figure 4** (December 2017) displays cooling and increased chlorophyll-a offshore. By February 2018 (**Figure 5**), SST reached its lowest, with offshore productivity shifting eastward—highlighting spatial displacement of productive zones during cooling events.

In the 2020–2022 La Niña, **Figure 6** (September 2020) shows SST warming unexpectedly high, but **Figure 7** (September 2021) and **Figure 8** (September 2022) demonstrate moderate SST with chlorophyll-a > 0.5 mg/m³ offshore. These spatial shifts suggest La Niña does not uniformly enhance upwelling but can create episodic productivity windows.

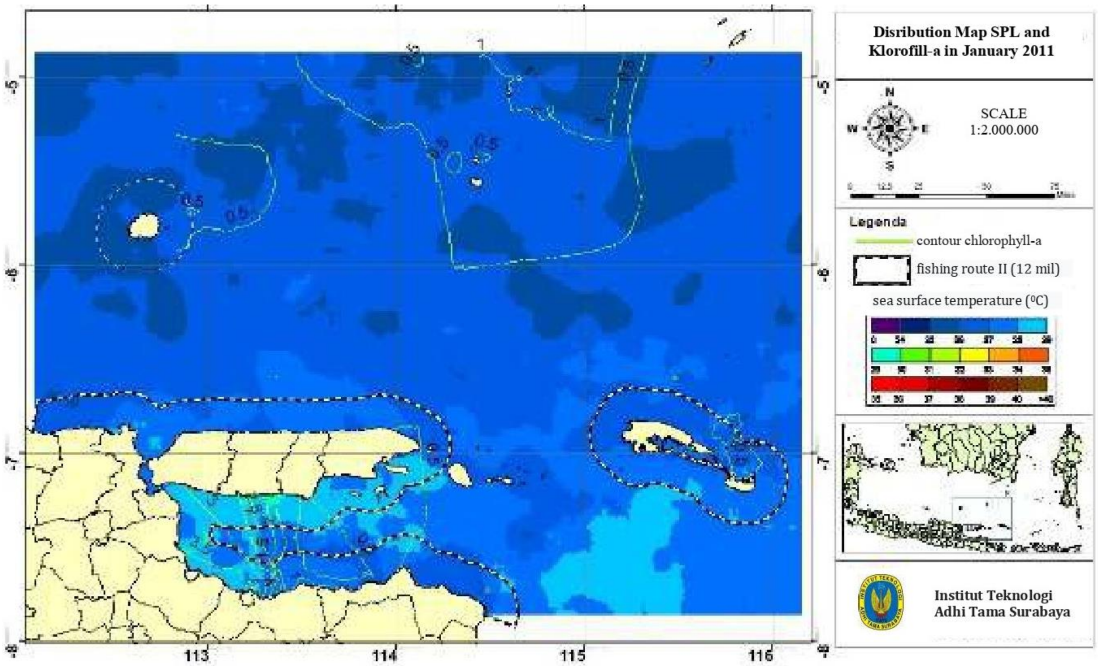

Figure 9. Distribution Map of SST and Chlorophyll-a in January 2021

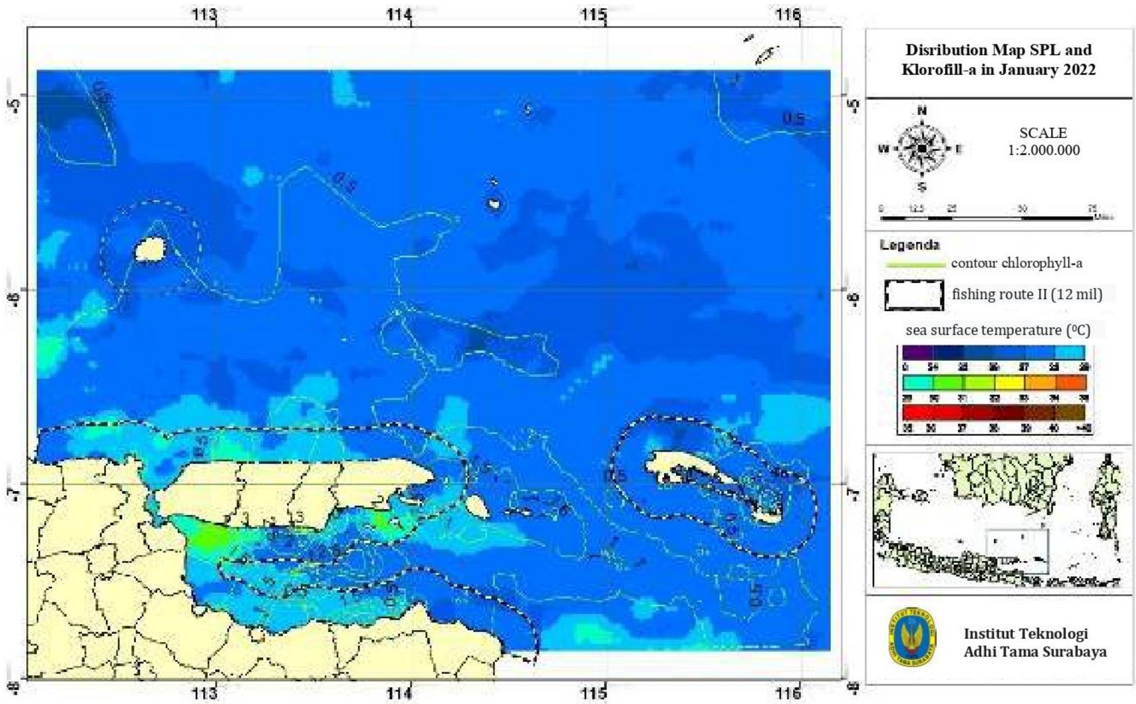

Figure 10. Distribution Map of SST and Chlorophyll-a in January 2022

3.5 Spatial Dynamics of SST and Chlorophyll-a during La Niña

3.5.1 October 2017–April 2018

Spatial SST and chlorophyll-a maps (**Figures 3–5**) show warm SSTs nearshore in November 2017, followed by cooling in December, with chlorophyll-a rising above 0.5 mg/m³ offshore. The lowest SST and highest offshore chlorophyll-a were seen in February 2018 (**Figure 5**), indicating delayed upwelling and nutrient redistribution consistent with Sidik et al. [1].

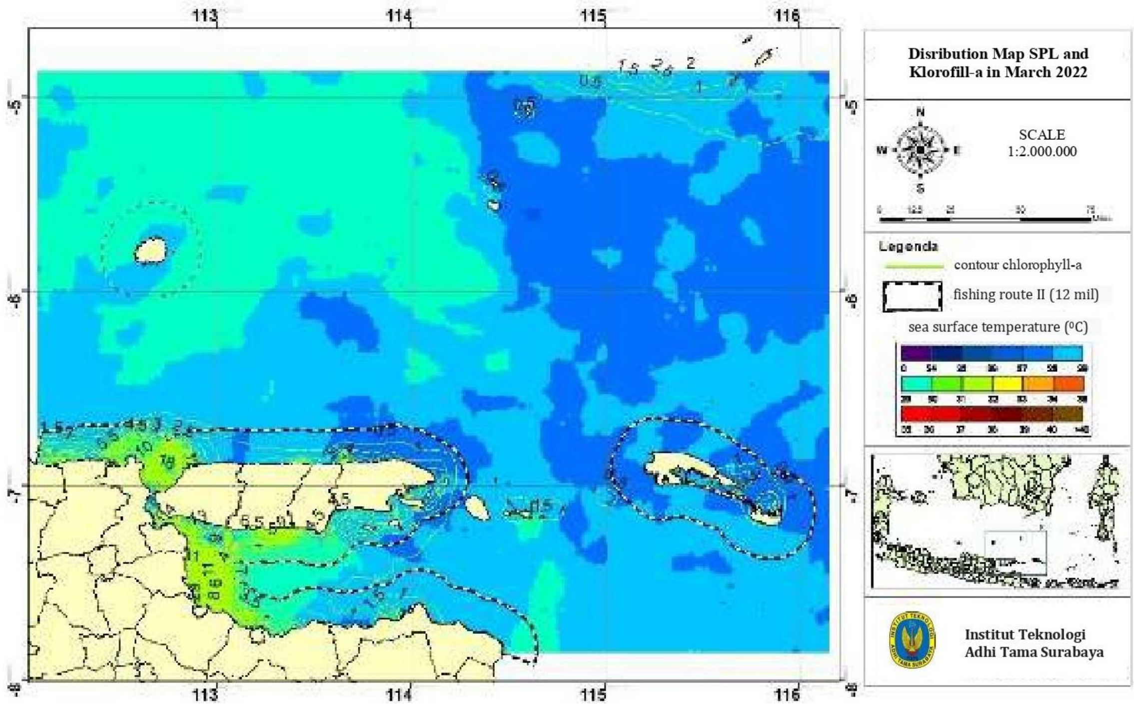

Figure 11. Distribution Map of SST and Chlorophyll-a in March 2022

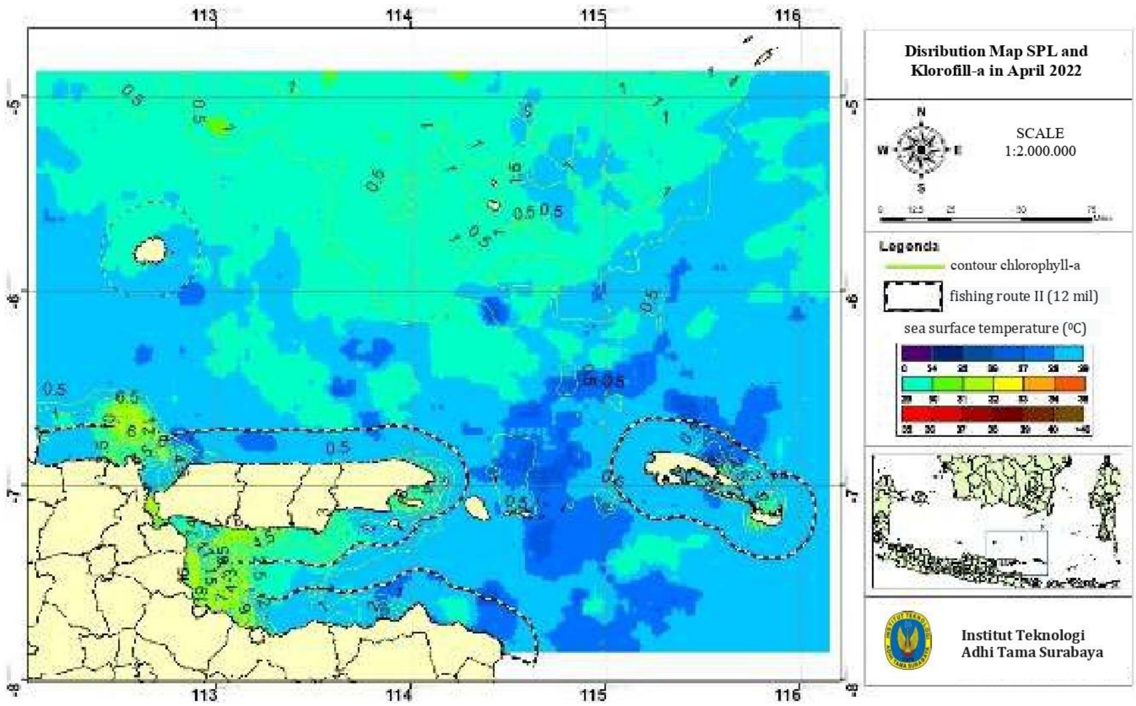

Figure 12. Distribution Map of SST and Chlorophyll-a in April 2022

3.5.2 August 2020–December 2022

SST and chlorophyll-a distributions in **Figures 6–8** show that September 2020 was anomalously warm, but by January 2021 (**Figure 9**) and January 2022 (**Figure 10**), offshore cooling occurred with chlorophyll-a exceeding 0.5 mg/m³. From March to May 2022 (**Figures 11–13**), SST increased, but chlorophyll-a remained high offshore, indicating persistent productivity due to delayed seasonal transitions. These spatial maps emphasize the importance of monitoring productivity "hotspots" beyond the 12-mile line, where fish often aggregate.

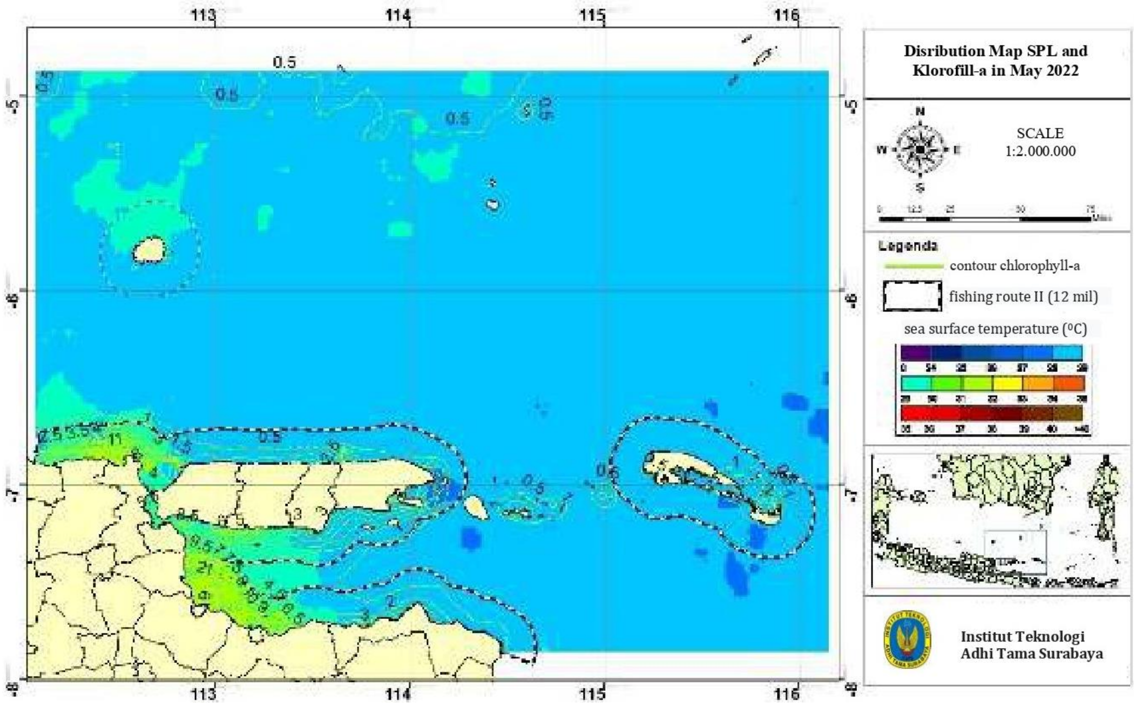

Figure 13. Distribution Map of SST and Chlorophyll-a in May 2022

4. Conclusion

This research has provided a comprehensive analysis of the spatiotemporal variability of **Sea Surface Temperature (SST)** and **chlorophyll-a concentration** in the northern waters of East Java during La Niña and El Niño periods between 2017 and 2022, with a specific focus on their relationship to **fisheries productivity**. The results highlight the significant but variable influence of the **La Niña phenomenon**, especially when coupled with **Indian Ocean Dipole (IOD)** phases, on the thermal and biological dynamics of the region's marine environment.

SST Variability and Ocean-Atmospheric Interactions; The **Eastern Monsoon** exhibited a consistent seasonal SST cycle, peaking in April and declining in August–September, with a recovery in October. While La Niña did not alter this seasonal rhythm, it contributed to a sustained rise in **SST anomalies**, particularly during the IOD(–) phase in 2020–2022. In contrast, in the **Western Monsoon**, La Niña events were associated with **suppressed SST anomalies**, reversing the typical warming trend for this season. These patterns suggest that La Niña's effects are **regionally dependent** and interact differently with prevailing monsoon systems. This spatial-seasonal discrepancy is crucial, as it underscores the need to **monitor climate phenomena in a seasonally disaggregated manner** to understand their ecological consequences more accurately.

Chlorophyll-a Dynamics and Biological Productivity; Chlorophyll-a, an indicator of phytoplankton abundance and thus primary productivity, displayed **non-uniform responses** to La Niña. In the first La Niña event (2017–2018), chlorophyll-a anomalies decreased—likely due to delayed or weakened upwelling and limited nutrient availability. Conversely, the later La Niña phase (2020–2022), particularly under **IOD(–)** conditions, was associated with a trend of **increasing chlorophyll-a anomalies**, especially in coastal and transitional zones.

These shifts imply that **chlorophyll-a response is not governed solely by SST**, but is instead the result of complex interactions involving thermocline depth, wind-induced mixing, and current-driven nutrient delivery. The enhanced chlorophyll-a observed in 2021–2022 could reflect **lagged biological responses** or local upwelling intensification due to negative IOD modulation.

SST and Chlorophyll-a Effects on Fish Catch; The interplay of SST and chlorophyll-a has a **direct influence on fish catch variability**. Statistical regression analysis demonstrated that **both parameters jointly contribute** to catch fluctuations. Higher catches were generally observed during El Niño and IOD(+) periods when SST was lower and chlorophyll-a was elevated—indicative of increased phytoplankton and favorable feeding conditions. In contrast, La Niña periods, despite occasionally high chlorophyll-a values, often yielded **lower catch volumes**, likely due to **thermal stress**, **displacement of fish populations**, or **lag effects** in ecosystem response.

Moreover, there is evidence of a **time lag**—estimated at approximately one month—between environmental change (e.g., SST and chlorophyll-a shifts) and catch outcomes. This reflects the **trophic cascade delay** in marine food webs, where the effects of phytoplankton blooms take time to reach higher trophic levels, such as pelagic fish targeted by fisheries.

Spatial Insights: Mapping SST and Chlorophyll-a during La Niña; Spatial analysis using satellite-derived SST and chlorophyll-a maps showed that La Niña years were characterized by **uneven fertility distribution**. While SST values tended to rise nearshore during the early La Niña months (e.g., November 2017), they decreased offshore later in the season (e.g., February 2018), triggering **localized increases in chlorophyll-a**. A similar trend was observed in 2020–2022, where offshore chlorophyll-a concentrations exceeded **0.5–1.0 mg/m³** in certain months, especially beyond the **12-nautical mile line**, as shown in **Figures 6 to 13**.

This offshore shift of productive zones implies that **key fishing grounds may relocate temporarily** due to La Niña conditions. Such dynamic changes pose a challenge to traditional fishing practices and highlight the need for **adaptive spatial planning** in marine resource management.

Fisheries and Management Implications; The findings indicate that the **La Niña phenomenon reduces marine fertility in some cases**, particularly during its early stages or when upwelling is not adequately triggered. This is evidenced by warmer SSTs, lower and spatially inconsistent chlorophyll-a distributions, and decreased fish catches. However, La Niña combined with IOD(–) may enhance productivity in some offshore zones, emphasizing the **importance of understanding climate interactions in multi-parameter contexts**.

These results hold practical significance for **fisheries management, policy-making, and climate adaptation strategies**:

a. **Identification of productive fishing zones** can be improved by monitoring SST and chlorophyll-a anomalies in near-real time using remote sensing.
b. Fishers and local authorities can use anomaly trends as **early warning indicators** for potential declines or shifts in catch zones.
c. Mitigation strategies, especially during La Niña, should consider both **coastal and offshore resource management**, as well as **alternative livelihoods** in periods of low productivity.

Recommendations for Future Research; To enhance the robustness and operational applicability of this study, future research should include:

a. **Field validation** of satellite-derived SST and chlorophyll-a data through in-situ measurements (e.g., CTD casts, plankton net sampling).
b. **Longer temporal coverage** (beyond 2022) to capture more ENSO cycles and better characterize multi-year anomalies (e.g., triple-dip La Niña events).
c. Integration of additional oceanographic and atmospheric parameters such as **rainfall, surface wind stress, ocean currents, wave height, and salinity**.
d. Development of **predictive ecological models** to estimate fish abundance and distribution using SST and chlorophyll-a as leading indicators.

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