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# SPATIOTEMPORAL PATTERNS OF HIGH MARINE PRODUCTIVITY IN THE MAKASSAR STRAIT BASED ON CHLOROPHYLL-A AND SEA SURFACE TEMPERATURE IN 2005–2025

Anisa Aulia Sabilah[1], Yasser Arafat[1], Asia[2], Irwan[1], Nurul Fitriani[1]

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[1]Marine Engineering Study Program, Bone Marine and Fisheries Polytechnic, South Sulawesi, Indonesia
[2]Fishing Engineering Study Program, Bone Marine and Fisheries Polytechnic, South Sulawesi, Indonesia
Corresponding Author:
*Anisa Aulia Sabilah
E-mail: anisaauliasabilah@poltekkpbone.ac.id

## ABSTRACT

The Makassar Strait serves as a crucial tropical marine corridor, exhibiting spatial and seasonal variations in productivity influenced by monsoon dynamics, ocean circulation, precipitation, and nutrient availability. This research delineated the spatiotemporal patterns of elevated chlorophyll-a concentrations in the Makassar Strait from 2005 to 2025, utilizing satellite-derived chlorophyll-a and Sea Surface Temperature (SST) data. Monthly datasets from Copernicus Marine and the Climate Data Store were examined at a resolution of 0.25° × 0.25°. High-productivity hotspots were identified using the monthly 75th percentile (P75) of chlorophyll-a, while climatological patterns and Pearson correlation analyses were employed to investigate temporal variability and its association with SST. High-productivity waters were predominantly located along the East Kalimantan coastal zone and the southern Makassar Strait, with local mean chlorophyll-a concentrations surpassing 0.5 mg $m^{-3}$. Domain-mean productivity reached a peak of approximately 0.31 mg $m^{-3}$ in March, whereas hotspot intensity was greatest in August (P75 = 0.220 mg $m^{-3}$). SST values ranged from 28.4 to 29.9 °C, exhibiting a significant warming trend of approximately 0.02 °C per year ($p = 0.00004$). Overall, SST and chlorophyll-a demonstrated a negative correlation ($r = -0.469$; $p < 0.05$), although this relationship varied across different months. The findings highlight recurring productivity hotspots and seasonal variability, which can facilitate marine productivity monitoring and further evaluation of fisheries potential in the Makassar Strait.

Keywords: chlorophyll-a, marine productivity, Makassar Strait, Sea Surface Temperature, temporal

## INTRODUCTION

Marine primary productivity constitutes a crucial element of tropical marine ecosystems, serving as the foundational energy source for higher trophic levels and being intricately linked to the distribution and potential abundance of fisheries resources. Chlorophyll-a is extensively employed as an indicator of phytoplankton biomass and marine primary productivity, as it represents the photosynthetic pigment of phytoplankton (Hanansyah et al., 2024). The spatial and temporal variability of chlorophyll-a is influenced by factors such as nutrient availability, light, water-column stability, freshwater input, and physical processes including vertical mixing and upwelling. The Makassar Strait, a strategically significant Indonesian waterway, connects the Pacific and Indian Ocean systems via the Indonesian Throughflow (ITF). Its oceanographic conditions are significantly impacted by monsoon forcing, circulation, and the seasonal redistribution of water masses (Cai et al., 2022; Furue et al., 2023). These processes can modify Sea Surface Temperature (SST), nutrient availability, and phytoplankton growth. Notably, seasonal cooling associated with upwelling can transport nutrient-rich subsurface water to the surface, thereby stimulating chlorophyll-a production, a phenomenon consistently observed in the southern part of the strait during the southeast monsoon (Graharto & Wulandari, 2022; Sabilah et al., 2026).

Previous research has demonstrated that SST and chlorophyll-a serve as effective indicators of oceanographic variability in the Makassar Strait. Graharto and Wulandari (2022) investigated SST, chlorophyll-a, and upwelling variability in the strait, while Elvianti et al. (2022) explored the relationship between upwelling areas and fisheries potential. Prior analyses identified a significant negative correlation between SST and chlorophyll-a (Pearson $r = -0.469$; $p < 0.05$) and highlighted the East Kalimantan coastal waters and southern Makassar Strait as regions of high productivity.

This study concentrates on high productivity as the primary focus of analysis, emphasizing its spatial distribution, seasonal development, intensity, and temporal recurrence, with SST serving as an environmental explanatory variable. The analysis also assesses the monthly P75 thresholds to quantify variations in hotspot intensity. The study aims to characterize the spatial and temporal distribution of high marine productivity in the Makassar Strait from 2005 to 2025, identify recurring hotspot areas and high-

productivity periods (distinguishing domain-mean productivity from hotspot intensity), and evaluate the relationship between productivity and SST at both pooled and monthly scales. The findings are anticipated to provide a spatially explicit foundation for monitoring marine productivity and supporting the interpretation of potential fisheries productivity in the Makassar Strait.

## MATERIALS AND METHODS

### Study area and period

The research focused on the Makassar Strait (Figure 1) and spanned the years 2005 to 2025. This 21-year timeframe facilitated the assessment of both seasonal and interannual productivity patterns.

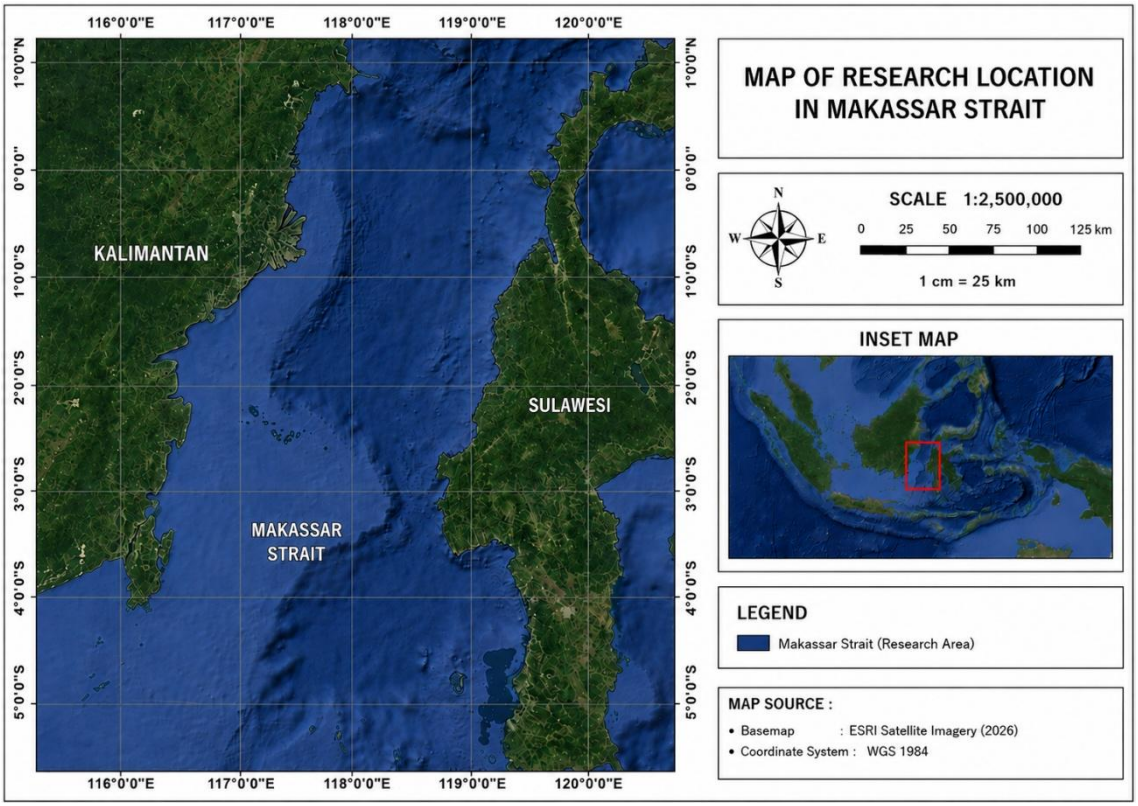



Figure 1. Map of research location in Makassar Strait

### Data sources

Two monthly gridded datasets, derived from satellite and reanalysis sources, were utilized. Sea Surface Temperature (SST) data were acquired from the Climate Data Store (CDS) in NetCDF format, featuring a spatial resolution of 0.25° × 0.25°. Similarly, Chlorophyll-a data were sourced from Copernicus Marine, also in NetCDF format and with a spatial resolution of 0.25° × 0.25°, serving as the primary indicator of phytoplankton abundance and marine productivity.

### Data processing

NetCDF data were processed utilizing Python in conjunction with Xarray, NumPy, Pandas, Matplotlib, and Cartopy. The processing sequence involved several steps: data acquisition, geographic subsetting to the Makassar Strait, quality control with the elimination of invalid values, conversion into analysis-ready arrays or data frames, computation of monthly means, spatial mapping, and temporal visualization. Subsequently, monthly composites were categorized into four seasonal periods: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON).

### Identification of productivity hotspots

High-productivity conditions were determined through the spatial distribution of chlorophyll-a. For each calendar month, a pixel was designated as a "hotspot" if its mean log10-chlorophyll-a value for the period 2005–2025 met or exceeded the 75th percentile (P75) of that month's spatial distribution within the study domain. This threshold is illustrated on each monthly panel and detailed in Table 1. As the threshold is recalculated monthly, it provides a relative (within-month) definition of "high," with the P75 value serving as a secondary index of productivity concentration for that month, independent of the proportion of the domain identified as a hotspot. Monthly hotspot maps were generated for January through December, followed by three-month seasonal composites and a multi-year mean hotspot map. The analysis focused on the persistence and spatial dynamics of high-chlorophyll regions, rather than interpreting chlorophyll-a as a direct indicator of carbon fixation.

Table 1. Monthly P75 chlorophyll-a hotspot threshold, Makassar Strait, 2005–2025 (mg $m^{-3}$)

| Month | P75 (mg $m^{-3}$) | Month | P75 (mg $m^{-3}$) |
|---|---|---|---|
| January | 0.198 | July | 0.206 |
| February | 0.205 | August | 0.220 (annual max) |
| March | 0.188 | September | 0.212 |
| April | 0.188 | October | 0.192 |
| May | 0.197 | November | 0.177 |
| June | 0.196 | December | 0.167 (annual min) |

### Temporal analysis

The climatological monthly productivity series, represented by the domain mean (Figure 4), was employed to discern the annual cycle. This series attains a peak of approximately 0.31 mg $m^{-3}$ in March and a trough of approximately 0.23 mg $m^{-3}$ in September. The monthly sequence was analyzed in conjunction with the seasonal hotspot maps and Table 1 to differentiate the timing of the domain-mean maximum from that of the hotspot-intensity maximum.

### Relationship with SST

The association between sea surface temperature (SST) and chlorophyll-a was evaluated using two complementary Pearson correlation analyses. The first analysis involved a pooled correlation across the entire monthly record from 2005 to 2025, yielding a correlation coefficient of $r = -0.469$, with statistical significance at $p < 0.05$. The second analysis entailed calculating a seasonal calendar of correlation coefficients for each calendar month over the 21-year period, as depicted in Figure 7. Additionally, a lag analysis was conducted, revealing the strongest negative correlation at a lag of 0 to approximately one month, with $r \approx -0.5$.

### Scope and interpretation

In this study, "high productivity" is defined operationally as chlorophyll-a values meeting or exceeding the monthly P75 threshold, as detailed in Table 1, within the specified study domain and period. This threshold represents a within-month relative percentile rather than a fixed absolute concentration. Consequently, a hotspot pixel may not correspond to the same absolute chlorophyll-a concentration across different months. Therefore, caution is advised when comparing hotspot areas across months. However, comparisons of the P75 value itself (Table 1) are directly interpretable as an index of monthly productivity intensity. This distinction is crucial for subsequent validation and future methodological refinement, such as by additionally reporting hotspot statistics against a fixed, calendar-independent absolute threshold.

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## RESULTS AND DISCUSSION

### Spatial pattern of high marine productivity

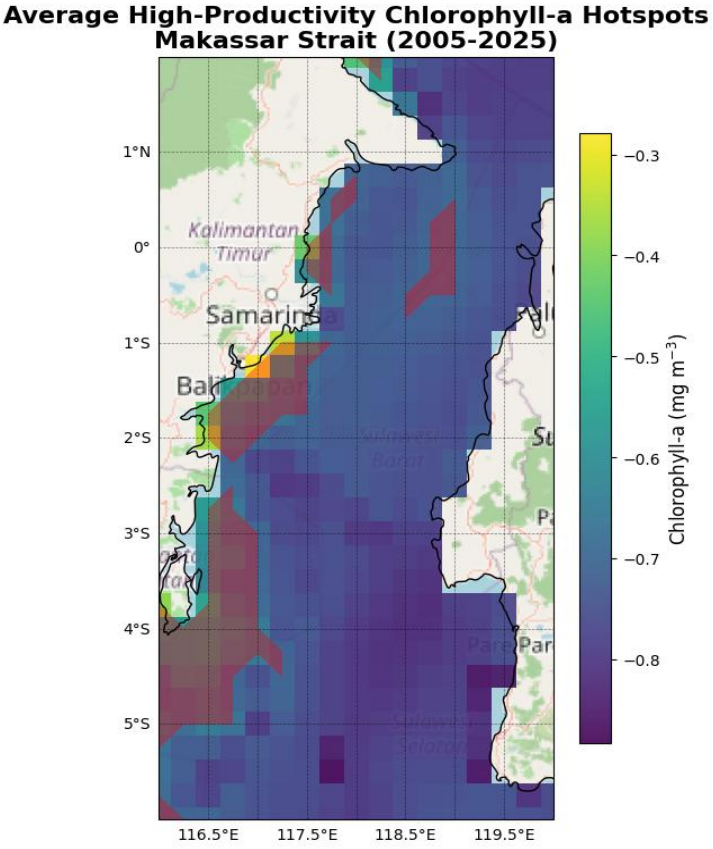



Figure 2. Mean high-productivity chlorophyll-a distribution, Makassar Strait, 2005–2025.

The mean distribution from 2005 to 2025 (Figure 2) indicates that high-productivity waters are predominantly located along the East Kalimantan coastal zone. This area extends from the Balikpapan region towards the southern Makassar Strait, where the local multi-year mean log10-chlorophyll-a is approximately −0.27 (≈0.53 mg m$^{-3}$), significantly exceeding the −0.55 to −0.85 (≈0.14–0.28 mg m$^{-3}$) typical of the central and offshore strait. The persistent hotspot polygons, shaded in red in Figure 4, delineate this coastal passage and include several detached diagonal bands further offshore in the northern half of the domain, as well as a broad block in the far south near the Sulawesi mainland coast.

The persistence of coastal hotspots suggests that productivity in the Makassar Strait is spatially heterogeneous. Coastal waters may receive nutrient inputs from terrestrial runoff and experience stronger physical mixing compared to offshore waters. Conversely, the deeper central strait is relatively oligotrophic. Consequently, the most productive areas are not uniformly distributed across the strait but are concentrated where nutrient supply and physical forces promote phytoplankton growth. This pattern aligns with recent regional syntheses of chlorophyll-a distribution around the Flores Sea, Java Sea, and Makassar Strait (Hanansyah et al., 2024).

The southern Makassar Strait constitutes a second significant productivity center, which is locally dominant in the September–November composite (Figure 4c). This region is characterized by cooler sea surface temperatures (SST) during the southeast monsoon and upwelling driven by southeasterly winds and the Indonesian Throughflow (ITF) outflow (Graharto & Wulandari, 2022; Sabilah et al., 2026). The concurrence of lower SST and increased chlorophyll-a provides a physical–biological signature indicative of nutrient enrichment from subsurface water.

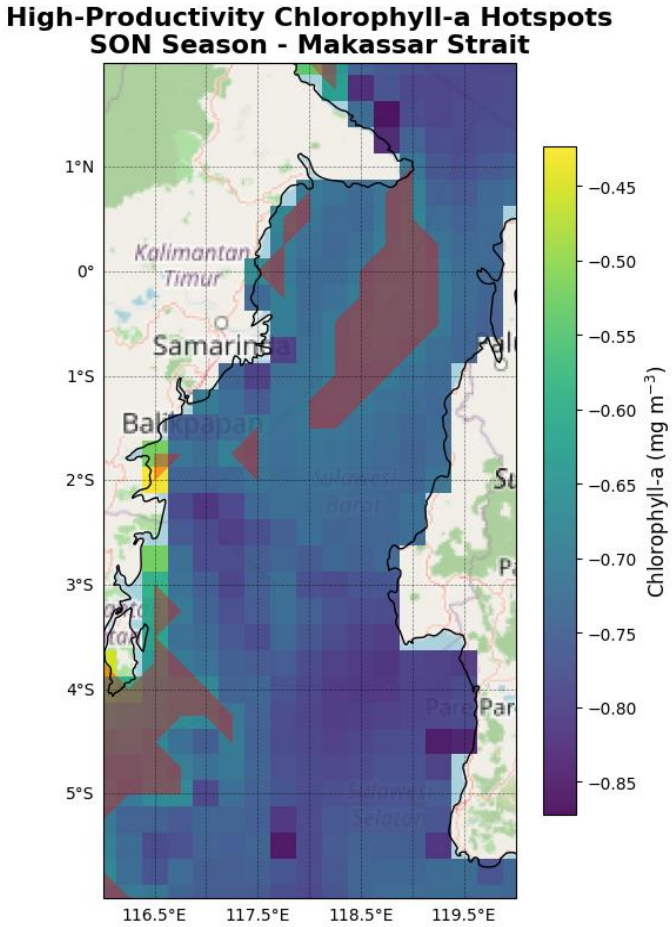



Figure 3. High-productivity chlorophyll-a hotspots, SON season, Makassar Strait.

During SON specifically (Figure 3), the local mean chlorophyll-a maximum near Balikpapan reaches approximately −0.43 log10 (≈0.37 mg m⁻³), again the single highest value in the domain for that season, with a second, smaller elevated patch near the southern tip of the strait (≈ −0.45 log10). Hotspot polygons in this composite are extensive both along the coast and offshore in diagonal bands across the northern strait, and form a large contiguous block in the south.

**Monthly evolution of productivity hotspots**

The monthly hotspot sequence (Figure 4a–c) shows a clear annual progression. During January–March, high-productivity areas were mainly concentrated near coastal waters, with the monthly P75 threshold ranging narrowly from 0.188 to 0.205 mg m⁻³ (Table 1). From April to June, the hotspot distribution became more spatially extensive, with diagonal offshore bands extending toward the central part of the strait, while the P75 threshold remained comparatively low (0.188–0.197 mg m⁻³) — i.e., the area classified as "high" widened even though the concentration that qualifies as "high" did not rise much. During July–September, both the spatial hotspot expression and the P75 threshold intensified together, and August recorded the highest monthly P75 threshold of the entire annual cycle (0.220 mg m⁻³), indicating that this is the month in which the top quartile of pixels reaches its most concentrated chlorophyll-a values, consistent with the well-documented peak of southeast-monsoon upwelling in the southern Makassar Strait during August (Sabilah et al., 2026) During October–December, the spatial hotspot pattern remained large — particularly a broad block in the southern strait in November and December — but the P75 threshold fell to its annual minimum in December (0.167 mg m⁻³), the lowest of any month. This combination means that late-year hotspots, while visually extensive, are defined against a lower concentration bar than the hotspots of the southeast-monsoon months; the two metrics should therefore be read together rather than the spatial extent alone being taken as a proxy for absolute productivity.

This monthly evolution demonstrates that productivity is controlled by more than a single persistent source. During the wet-season months, coastal productivity can be supported by freshwater and nutrient inputs,

whereas during the southeast monsoon the southern strait becomes increasingly influenced by physical processes that enhance nutrient availability. The July–September enhancement documented here is specifically associated with the southeast monsoon and upwelling, matching independent studies reporting an August upwelling peak in the southern Makassar Strait with chlorophyll-a increases of comparable magnitude (Sabilah et al., 2026).

The monthly hotspot sequence is therefore characterized by a shift from predominantly coastal productivity toward broader, more offshore-influenced, and more *intense* (higher P75) productivity during the middle of the year, followed by a retreat toward coastal zones — but at lower absolute concentration — late in the year. Such seasonal displacement is important when using chlorophyll-a maps as indicators of fisheries productivity because a single annual mean, or a hotspot map read for spatial extent alone, can obscure both the timing and the intensity of the most productive conditions.

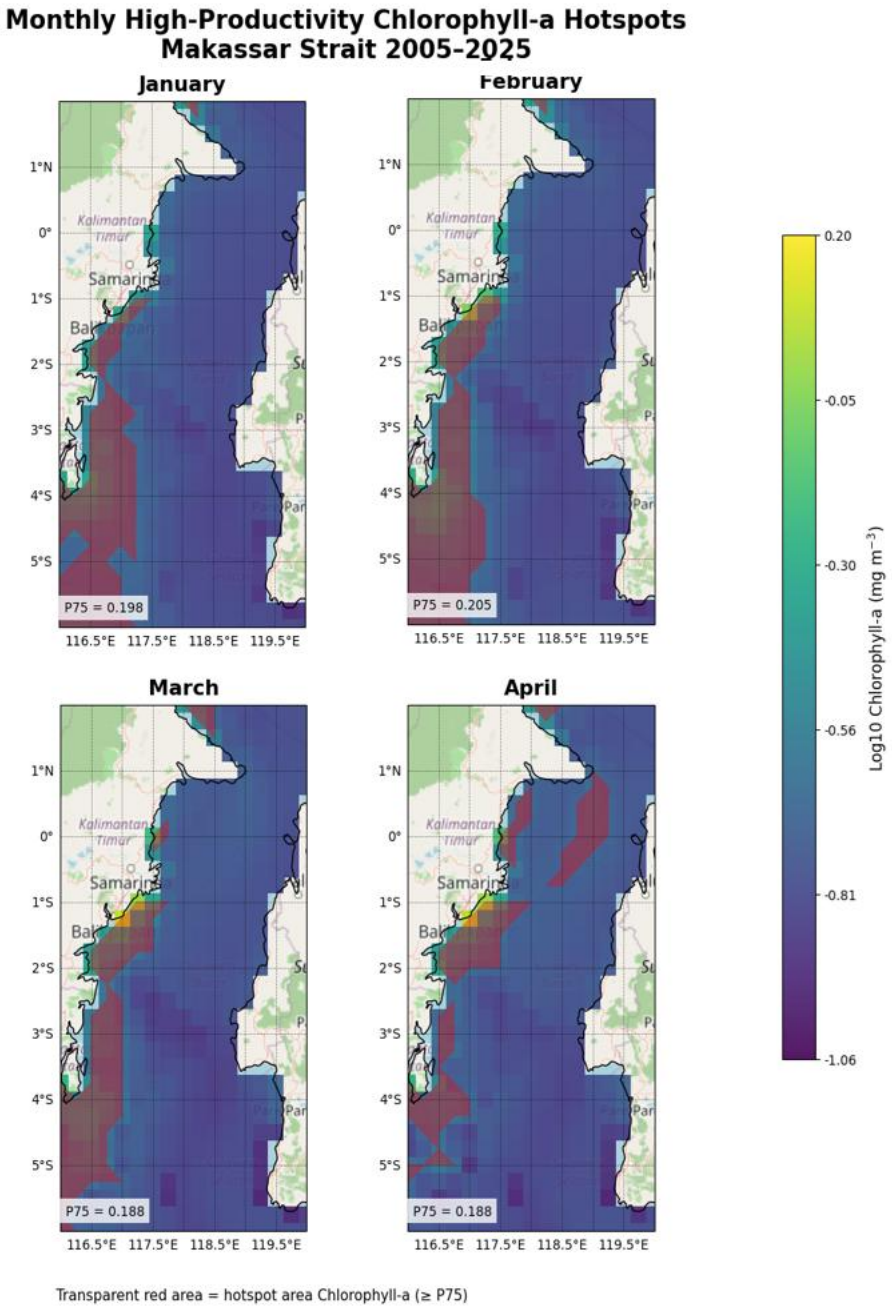



Figure 4a. Monthly high-productivity chlorophyll-a hotspot maps, January–April, 2005–2025.

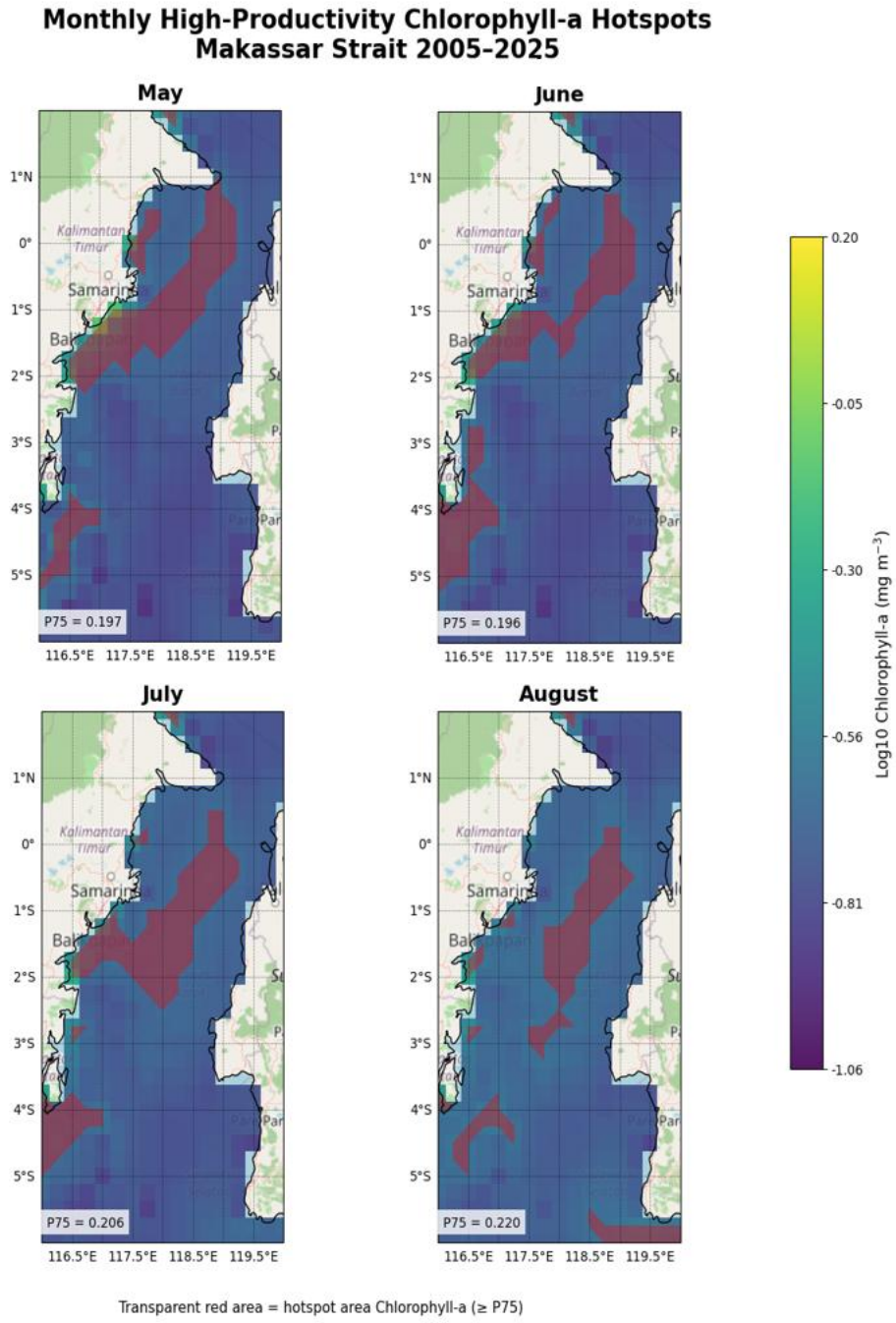



Figure 4b. Monthly high-productivity chlorophyll-a hotspot maps, May–August, 2005–2025.

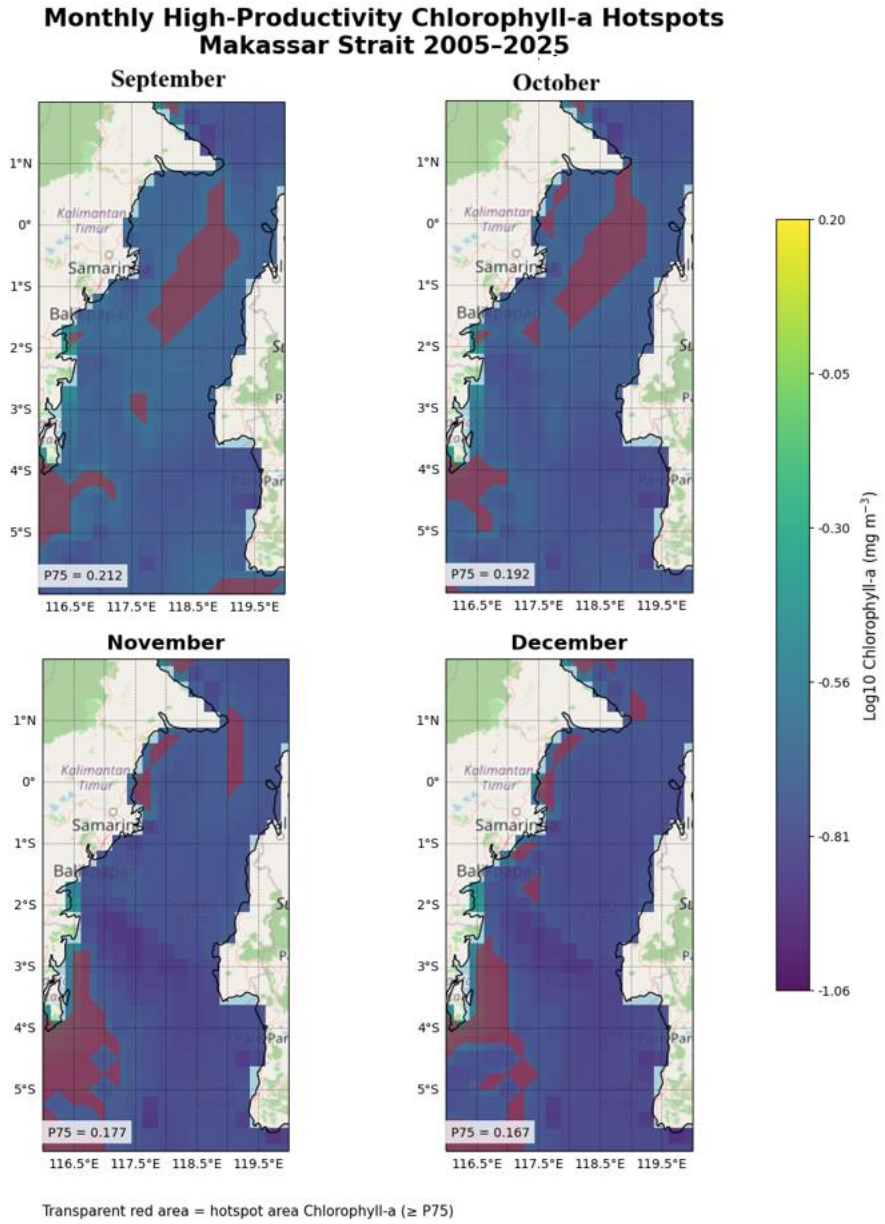



Figure 4c. Monthly high-productivity chlorophyll-a hotspot maps, September–December, 2005–2025.

### Seasonal pattern and productivity calendar

The seasonal productivity calendar (Figure 5, domain-mean chlorophyll-a by year and month) underscores the seasonal nature of productivity, demonstrating a broadly stable pattern over the 21-year record. Higher productivity, indicated by darker shading, consistently occurs from January to April in nearly every year from 2005 to 2025, whereas the period from June to October consistently exhibits the palest shading, indicative of lower productivity. A significant finding from the productivity calendar is the identification of February to April as the period of highest climatological productivity, consistently represented as the darkest high-productivity category in almost every individual year, not merely in the multi-year mean. This suggests that the seasonal pattern is a robust, recurring feature rather than an anomaly of a few years. Conversely, June to October generally displays lower climatological productivity, although certain years (e.g., 2013, 2016, and 2021) show a noticeable secondary increase in productivity during June and July, aligning with interannual upwelling variability. Productivity rises again during November and December with the onset of the rainy season.

This finding should be differentiated from the spatial hotspot result previously described. The climatological time series reveals a domain-mean maximum around March, whereas the monthly hotspot threshold (Table 1) indicates the most concentrated hotspot expression during July to September, particularly in August. These findings are not contradictory; a high domain-average productivity value and a high hotspot-intensity threshold reflect different aspects of the productivity field. March represents the peak domain-mean value in the time series, while August signifies the peak localized/hotspot expression in the monthly maps. This distinction is explicitly made here for the first time by directly reading the P75 values from the hotspot figures, rather than treating the hotspot maps solely qualitatively.

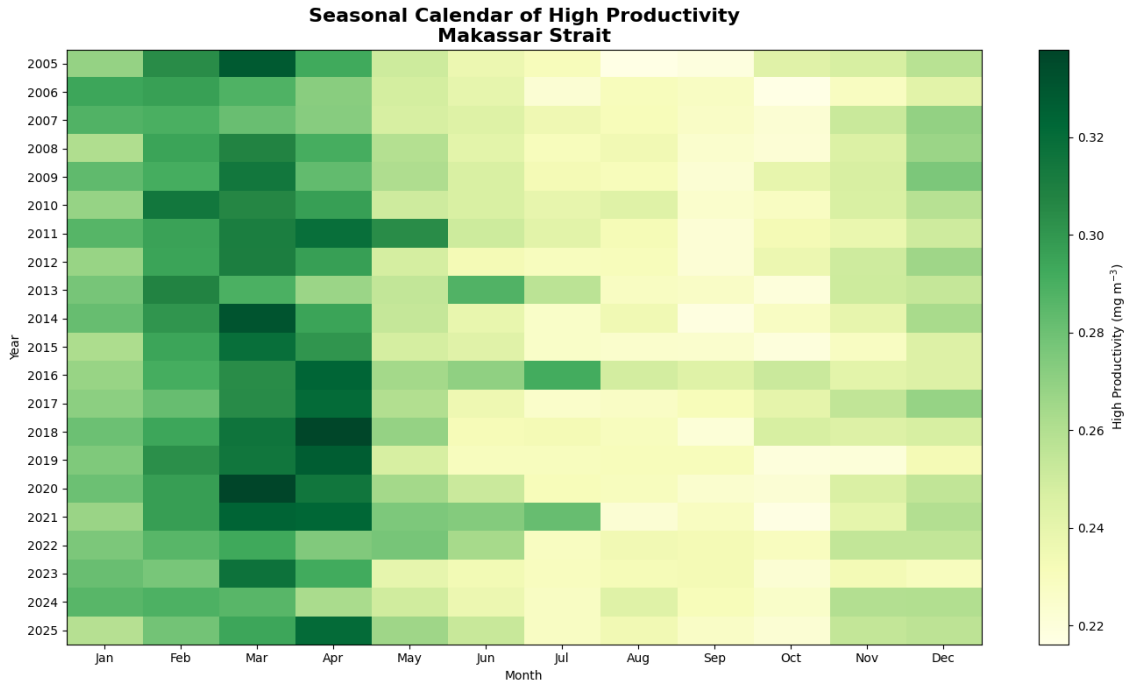



Figure 5. Seasonal calendar of high productivity, Makassar Strait, 2005–2025.

## Temporal magnitude of productivity

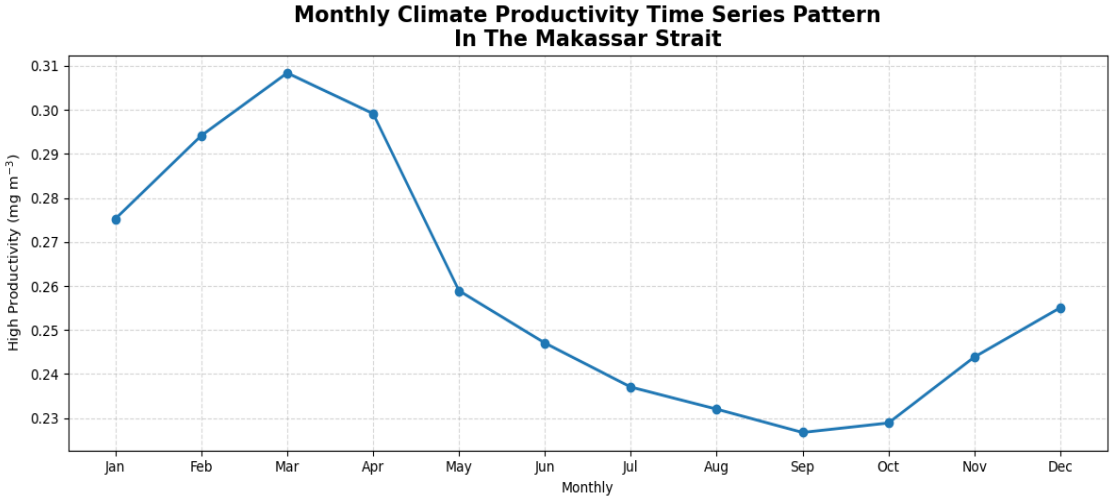



Figure 6. Monthly climatological productivity time series, Makassar Strait, 2005–2025.

The monthly productivity series (Figure 6) indicates an increase from approximately 0.275 mg $m^{-3}$ in January to a peak of about 0.308 mg $m^{-3}$ in March. Productivity levels remained relatively high through April, at approximately 0.299 mg $m^{-3}$, before progressively declining from May to August, reaching a minimum of around 0.226 mg $m^{-3}$ in September. Subsequently, productivity increased towards October (

≈0.229 mg $m^{-3}$), November (≈0.244 mg $m^{-3}$), and December (≈0.255 mg $m^{-3}$). The increase observed from January to April is likely linked to rainfall, mixing, and enhanced nutrient availability during the wet season and its transition. Conversely, the September minimum is associated with a reduced nutrient supply to the surface and increased water-column stability during the driest period of the year.

The annual cycle thus suggests two phases of productivity enhancement: a primary climatological maximum during the wet-season-to-transition period, centered around March, and a secondary increase towards the end of the year, around November to December. Furthermore, the spatial hotspot analysis reveals a pronounced productivity-intensity phase along the coast and southern regions from July to September, particularly in August. Collectively, these findings suggest that productivity in the Makassar Strait exhibits both a domain-scale temporal maximum in March and a seasonally migrating, intensity-based spatial maximum in August, which do not coincide within the same month.

**Relationship between SST and high productivity**

The sea surface temperature (SST) ranged from 28.4 to 29.9 °C between 2005 and 2025, with higher temperatures observed in the central and eastern regions of the strait, and lower temperatures in the southern sector. A statistically significant long-term warming trend of approximately 0.02 °C per year was identified ($p = 0.00004$). This rate aligns with regional and global evaluations of tropical sea surface warming and the increased occurrence of marine heatwave conditions in Indo-Pacific waters over the past decade (Capotondi et al., 2024).

The aggregated Pearson correlation between SST and chlorophyll-a throughout the entire dataset was negative and significant ($r = -0.469$; $p < 0.05$). This finding suggests that periods or locations with reduced surface temperatures were associated with elevated chlorophyll-a levels. This pattern supports the hypothesis that seasonal upwelling introduces cooler, nutrient-rich water into the surface layer, thereby promoting phytoplankton growth.

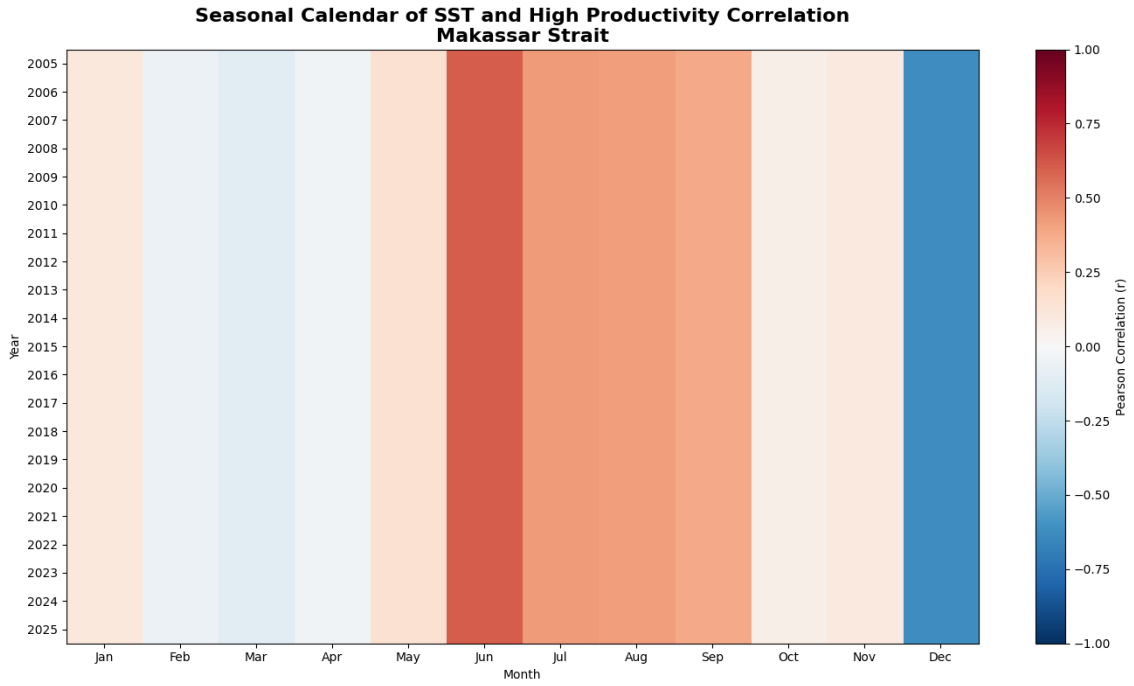



Figure 7. Seasonal calendar of SST–chlorophyll-a correlation, Makassar Strait, 2005–2025.

However, the seasonal correlation calendar (Figure 7), which recalculates the SST–chlorophyll-a Pearson correlation for each calendar month over 21 years, indicates that the pooled negative statistic does not accurately represent most individual months. An examination of the calendar reveals the following: January exhibits a weak positive correlation ($r \approx +0.2$–$0.3$); February through April are nearly neutral, with a slight negative tendency ($r \approx 0$ to $-0.3$, with March being the most negative); May returns to a weak positive correlation ($r \approx +0.2$); June demonstrates the strongest positive correlation of the year ($r \approx +0.7$ – $0.8$); July to September maintain a moderate positive correlation ($r \approx +0.4$ – $0.55$); October and November show

only a weak positive correlation ($r \approx 0$–$0.2$); and December is notably the strongest and only clearly negative month ($r \approx -0.7$ to $-0.8$). Thus, in most months, years with anomalously warm SST tend to have higher chlorophyll-a levels, contrary to the pooled statistic. The strong negative correlation in December, along with the general seasonal pattern (cooler months generally having higher chlorophyll-a than warmer months), contributes to the negative pooled correlation. This distinction between within-season (interannual) and pooled, across-season relationships is typical of tropical SST–chlorophyll statistics and suggests caution when using the pooled r as a sole indicator of the SST–productivity coupling mechanism. A plausible explanation is that interannual SST anomalies in most months are partially influenced by ENSO/IOD-related changes in wind-driven upwelling and ITF transport, which may co-vary with chlorophyll-a anomalies in a given month (Cai et al., 2022; Iskandar et al., 2024).

The lag analysis supports the upwelling interpretation, as the strongest negative association across the pooled record was observed at a lag of 0 to approximately one month ($r \approx -0.5$). This short response interval aligns with a rapid biological response following nutrient enrichment, although chlorophyll-a is affected by multiple processes, and correlation alone does not imply causation. Including additional variables such as salinity, current velocity, wind, rainfall, and sea-level anomaly would aid in disentangling these seasonal and interannual signals (Mahdiana & Paradhita, 2024; Rahman & Rahaman, 2024; Siahaan & Wijaya, 2024).

**Oceanographic interpretation of productivity hotspots**

The concentration of high-productivity zones in the coastal waters of East Kalimantan can be attributed to the combined influence of terrestrial and oceanographic nutrient sources. Nutrients are supplied through coastal runoff and riverine inputs, while mixing processes redistribute these nutrients within the surface layer. In the southern Makassar Strait, seasonal upwelling associated with the southeast monsoon and the Indonesian Throughflow is likely the primary mechanism (Cai et al., 2022; Furue et al., 2023). This upwelling results in surface cooling and nutrient enrichment, which plausibly accounts for the observed increase in chlorophyll-a levels and aligns with independent moored and modeled estimates of ITF transport variability and its interaction with regional wind forcing (Iskandar et al., 2023).

The productivity pattern in the Makassar Strait thus reflects the interaction between two primary mechanisms: coastal enrichment and oceanographic enrichment related to upwelling and the ITF. Coastal enrichment is particularly significant during wet-season conditions, whereas oceanographic enrichment becomes more pronounced and spatially concentrated (Table 1) during the southeast monsoon. The relative contributions of these mechanisms vary across space and time, explaining why the highest productivity is not restricted to a single location or month, and why the domain-mean and hotspot-intensity maxima occur in different months (March and August, respectively).

From a marine-resource perspective, recurring productivity hotspots serve as ecological indicators of areas with increased phytoplankton biomass and potentially greater food availability for higher trophic levels. However, high chlorophyll-a concentrations should not be directly equated with high fish abundance or catch rates. Fisheries distributions are also influenced by habitat, prey composition, temperature preferences, currents, oxygen levels, fishing effort, and species-specific behavior. Therefore, the current productivity map should be regarded as an environmental baseline for further analysis of fisheries potential rather than a direct map of fishing grounds.

**Implications for monitoring and marine resource management**

The identification of consistently high-productivity regions serves as a practical foundation for prioritizing oceanographic monitoring efforts. The coastal sector of East Kalimantan should be monitored throughout the year due to its consistently elevated mean chlorophyll-a levels (Figure 2). In contrast, the southern Makassar Strait requires focused attention during the months of July to September, when both the intensity of hotspots (Table 1) and their spatial extent reach their peak. Monitoring efforts can be enhanced by integrating chlorophyll-a and sea surface temperature (SST) data with additional parameters such as wind stress, rainfall, salinity, sea-level anomalies, current velocity, and in situ nutrient observations. Furthermore, the current within-month relative (P75) hotspot classification should be supplemented with a fixed absolute threshold to facilitate direct comparisons across years and months (Mahdiana & Paradhita, 2024; Rahman & Rahaman, 2024; Siahaan & Wijaya, 2024).

The 21-year dataset provides a baseline for assessing future changes. The observed SST warming trend of approximately 0.02 °C per year suggests alterations in the physical background state of the strait, consistent

with broader warming trends in the Indo-Pacific region and the occurrence of marine heatwaves (Capotondi et al., 2024). Continued monitoring is crucial to ascertain whether the spatial extent, intensity (P75 threshold), or seasonal timing of productivity hotspots is affected by long-term warming and climate variability. Additionally, it is important to determine whether the interannual SST–chlorophyll-a relationship observed for individual months (Figure 6) remains stable or undergoes shifts due to changing ENSO/IOD regimes (Cai et al., 2022; Iskandar et al., 2024).

## CONCLUSIONS

Marine productivity in the Makassar Strait from 2005 to 2025 was predominantly concentrated in the coastal waters of East Kalimantan and the southern part of the strait, whereas the central offshore region generally exhibited lower chlorophyll-a concentrations. The intensity of productivity hotspots was greatest during July to September, with a peak in August, while the domain-mean chlorophyll-a concentration reached its maximum during February to April. Sea surface temperature (SST) ranged from 28.4 to 29.9 °C, displaying an upward trend of approximately 0.02 °C per year. Overall, SST was inversely correlated with chlorophyll-a ($r = -0.469$; $p < 0.05$), suggesting that cooler surface conditions were typically associated with higher productivity. These findings underscore the distinct spatial and seasonal variability in marine productivity and establish a baseline for monitoring productivity in the Makassar Strait. Future research should incorporate in situ observations and additional physical and biogeochemical variables to more comprehensively explain the observed variability.

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REFERENCES

Arifin, W. A., Ode, L., Minsaris, A., Anzani, L., Ramadhani, T. S., Grace, M., Lubis, A., Dzikrillah, A., & Suprianto, O. (2025). Pemetaan lamun menggunakan algoritma machine learning dengan citra Sentinel-2A. 18(1): 40–47.

Arjuno Yo Indarto, D. A. S. (2026). Analisis pengaruh parameter oseanografi terhadap nilai produktivitas primer bersih di Perairan Selat Makassar dan Perairan Laut Arafura. 19(1): 70–81.

Ashari, F., Redjeki, S., & Kunarso, K. (2014). Keterkaitan Jumlah Tangkapan Ikan Pelagis Kecil Dengan Distribusi Klorofil-A dan Suhu Permukaan Laut Menggunakan Citra Modis di Laut Jawa Dan Selat Makassar. Journal of Marine Research, 3(3), 366-373. https://doi.org/10.14710/jmr.v3i3.6009

Andrew SM, Morell HT, Strzepek RF, Boyd PW and Ellwood MJ (2019) Iron Availability Influences the Tolerance of Southern Ocean Phytoplankton to Warming and Elevated Irradiance. Front. Mar. Sci. 6:681. doi: 10.3389/fmars.2019.00681

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.-S., Lengaigne, M., McPhaden, M. J., Stuecker, M. F., Taschetto, A. S., Timmermann, A., Wu, L., Yeh, S.-W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X.-T., Bayr, T., Brown, J. R., Capotondi, A., Cobb, K. M., Gan, B., Geng, T., Ham, Y.-G., Jin, F.-F., Jo, H.-S., Li, X., Lin, X., McGregor, S., Park, J.-H., Stein, K., Yang, K., Zhang, L., & Zhong, W. (2022). Indonesian Throughflow variability and linkage to ENSO and IOD in an ensemble of CMIP5 models. Journal of Climate, 35(10). https://doi.org/10.1175/JCLI-D-21-0485.1

Capotondi, A., Rodrigues, R. R., Gupta, A. Sen, Benthuysen, J. A., Deser, C., Frölicher, T. L., Lovenduski, N. S., & Amaya, D. J. (2024). A global overview of marine heatwaves in a changing climate. Communications Earth & Environment. https://doi.org/10.1038/s43247-024-01806-9

Elvianti, N., Muhiddin, A. H., & Zainuddin, M. (2022). On the relationship between area of upwelling and potential. 7: 29–33.

Furue, R., Nonaka, M., & Sasaki, H. (2023). The intrinsic variability of the Indonesian Throughflow. Frontiers in Marine Science, 10:1117304. https://doi.org/10.3389/fmars.2023.1117304

Graharto, S. R., & Wulandari, S. Y. (2022). Identifikasi variabilitas suhu permukaan laut dan klorofil-a serta intensitas upwelling di Selat Makassar. Buletin Oseanografi Marina, 11(2): 206–214. https://doi.org/10.14710/buloma.v11i2.42170

Hanansyah, M. P., et al. (2024). Spatio-temporal variation of chlorophyll-a around the Flores Sea, Java Sea, and Makassar Strait and its relationship with temperature and salinity. IOP Conference Series: Earth and Environmental Science, 1418: 012036. https://doi.org/10.1088/1755-1315/1418/1/012036

Hoyer, S., & Hamman, J. J. (2017). xarray: N-D labeled arrays and datasets in Python. Journal of Open Research Software.

Iskandar, I., Mardiansyah, W., Lestari, D. O., Sari, Q. W., & Setiawan, R. Y. (2023). Effects of high-frequency flow variability on the pathways of the Indonesian Throughflow. Journal of Geophysical Research: Oceans. https://doi.org/10.1029/2022JC019610

Iskandar, I., Sari, Q. W., Setiawan, R. Y., Siswanto, E., Ishizaka, J., Bahiyah, A., Mardiansyah, W., & Puryajati, A. D. (2024). Seasonal and interannual variations of surface chlorophyll-a in the Karimata Strait. International Journal of Remote Sensing, 45(23): 8905–8918. https://doi.org/10.1080/01431161.2023.2266123

Mandal, S., & Susanto, R. D. (2022). On investigating the dynamical factors modulating surface chlorophyll-a variability along the South Java Coast.

Mahdiana, I., & Paradhita, L. (2024). Spatio temporal distribution of SST and chlorophyll-a in WPP 718 waters during the west season: A case study of Merauke Regency waters. 26(8): 47–54.

Rahman, R., & Rahaman, H. (2024). Evaluation of Sea Surface Temperature from ocean reanalysis products over the North Indian Ocean. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2024.1461696

Robinson, I. S. (2016). Discovering the Ocean from Space: The Unique Applications of Satellite Oceanography. Springer.

Sabilah, A. A., Hawati, H., Ismail, I., Jamil, K., & Wahira, W. (2026). Pemetaan Variabilitas Suhu Permukaan Laut dan Klorofil-A Berbasis Citra Aqua Modis di Perairan Spermonde, Selat Makassar. *Jurnal Salamata*, *8*(1), 34-44.

Siahaan, J. E. V., & Wijaya, Y. J. 2024. Variasi temporal dinamika upwelling di Selat Makassar periode 2007–2021. Buletin Oseanografi Marina, 13(1): 122–135. https://doi.org/10.14710/buloma.v13i1.55838