International Journal of Engineering Science and Advanced Technology (IJESAT)
Vol 26 Issue 06, June 2026
Received: 20-04-2026 Accepted: 28-05-2026 Published: 04-06-2026

THE EFFECT OF WIND SPEED ON SEA SURFACE TEMPERATURE VARIATIONS IN THE WATERS OF BANYUWANGI, INDONESIA

Novian P.K, Bayu M.

Study Program of Fisheries and Marine Technology and Business, Faculty of Fisheries and Marine Sciences,
Diponegoro University, Indonesia

ABSTRACT

Sea Surface Temperature (SST) is an important oceanographic parameter that plays a major role in atmosphere–ocean interactions and influences regional ocean dynamics. Variability of SST in tropical regions is strongly affected by wind-driven processes such as vertical mixing, Ekman transport, and upwelling. The southern waters of Banyuwangi, located in the eastern Indian Ocean, are influenced by seasonal monsoon systems and exhibit complex oceanographic conditions. However, studies examining SST variability in this region by integrating surface and subsurface parameters remain limited. Therefore, this study aimed to analyze the influence of wind forcing on SST variability in the southern waters of Banyuwangi using SST, surface wind, and vertical density profile data. SST data were obtained from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), wind data were derived from ASCAT products, and density profiles were calculated from temperature and salinity datasets. The analysis was conducted using spatial–temporal approaches, Hovmöller diagrams, and Pearson correlation analysis. The results showed a clear seasonal SST pattern during 2025, with warmer conditions (>29 °C) occurring during January–May and October–December, while lower SST values (~26–27 °C) occurred during June–September. The cooling period coincided with increased wind intensity during the southeast monsoon season, when wind speed reached approximately 5–6 $m\ s^{-1}$. Density profiles showed upward displacement of isopycnal layers during June–September, indicating shoaling of denser subsurface waters toward shallower depths. Pearson correlation analysis revealed a moderately strong negative relationship between wind speed and SST ($r = -0.68$), indicating that stronger winds were associated with lower SST conditions. These findings suggest that monsoon-driven wind forcing plays an important role in controlling seasonal SST variability in the southern waters of Banyuwangi through wind-induced vertical ocean processes.

Keywords: Banyuwangi, SST, Wind, Density, Upwelling

INTRODUCTION

Sea Surface Temperature (SST) is one of the most important oceanographic parameters that plays a significant role in regulating atmosphere–ocean interactions (Kramer and Karnauskas, 2025). SST variability influences ocean circulation, primary productivity, weather formation, and regional to global climate variability. Variations in SST in tropical regions are strongly influenced by atmosphere–ocean dynamic processes, one of which is the transfer of wind momentum at the ocean surface. Surface winds can modify ocean conditions through vertical mixing, Ekman transport, and upwelling–downwelling processes, which directly affect temperature distribution in both surface and subsurface ocean layers (Martono, 2016).

The southern waters of Banyuwangi are part of the eastern Indian Ocean and exhibit complex oceanographic characteristics (Tang et al., 2022). This region is influenced by the Asian–Australian monsoon system, regional climate variability such as the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD), as well as the dynamics of the Indonesian Throughflow (ITF). Seasonal variations in wind patterns alter the intensity of surface wind stress, which may regulate upwelling formation along the southern coasts of Java and Bali. This upwelling phenomenon is often associated with a decrease in SST due to the uplift of colder subsurface water masses toward the surface (deCastro et al., 2014).

Previous studies have shown that the southern waters of Java and Bali experience a significant decline in SST during the southeast monsoon season when southeasterly winds become stronger (Rachman et al., 2024). The intensification of winds during this period enhances offshore Ekman transport, thereby triggering coastal upwelling. However, the response of SST to changes in wind patterns is not solely controlled by surface processes but is also influenced by the vertical structure of the water column. Vertical water mass characteristics, such as density distribution and thermal stratification, can determine the efficiency of mixing processes and water mass transport toward the surface (Horii et al., 2016).

In addition, Ekman Mass Transport (EMT) serves as an important indicator for describing ocean responses to surface wind forcing. EMT can explain both the direction and magnitude of water mass transport driven by winds and can therefore be used to identify transport mechanisms contributing to SST variability. The combination of EMT analysis and vertical density profiles allows a more comprehensive evaluation of the physical mechanisms linking wind forcing and SST variations (Simanjuntak and Lin, 2022).

Although several studies have investigated the relationship between winds and upwelling in the southern Java–Bali region, specific studies examining the influence of wind on SST variability in the southern waters of Banyuwangi while considering EMT and vertical density structures remain limited. An integrated approach using both surface and subsurface parameters is therefore necessary to improve understanding of oceanographic dynamics in this region. Therefore, this study aims to analyze the influence of wind on SST variability in the southern waters of Banyuwangi, Indonesia, using SST, surface wind, EMT, and vertical density

International Journal of Engineering Science and Advanced Technology (IJESAT)
Vol 26 Issue 06, June 2026
Received: 20-04-2026 Accepted: 28-05-2026 Published: 04-06-2026

profile data. The results of this study are expected to provide a better understanding of atmosphere–ocean interactions in southern Indonesian waters and serve as a basis for further studies of regional oceanographic dynamics.

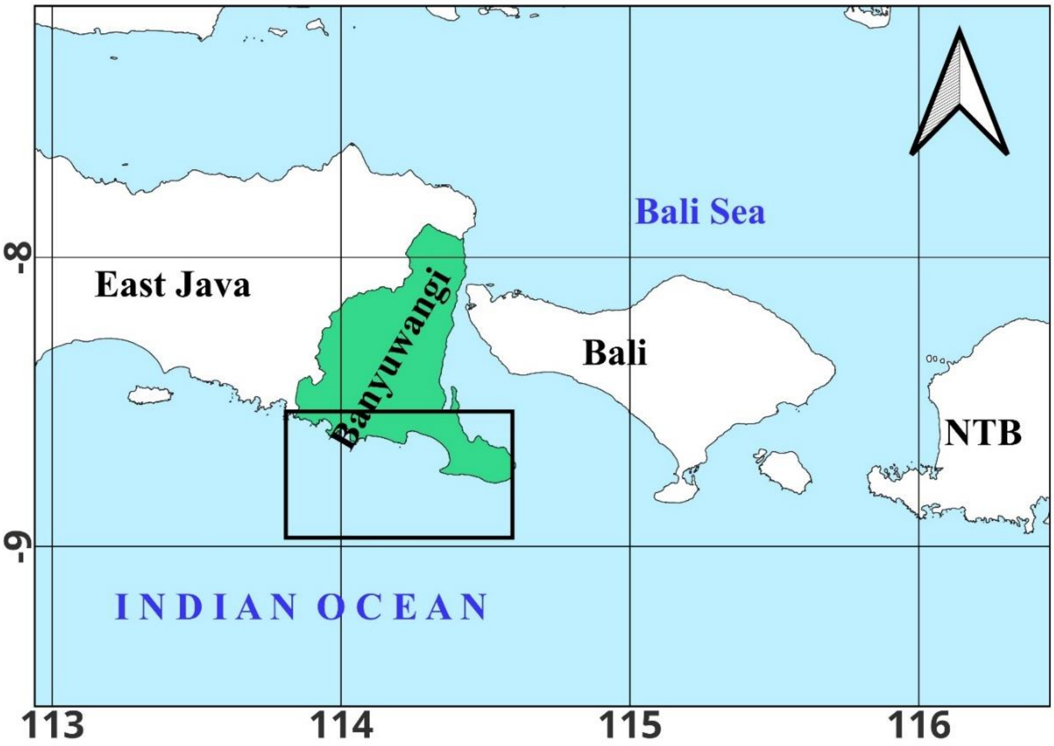

Figure 1. Research location in the waters of Banyuwangi Regency, East Java, Indonesia. Black box represents the area of interest.

METHODOLOGY

The sea surface temperature data used is sourced from the Operational Sea Surface Temperature and Ice Analysis (OSTIA). This dataset, with a spatial resolution of 0.05° x 0.05° and L4 level, is generated through an assimilation process that combines satellite data with in-situ observations from buoys and ships (Good et al., 2020; Redfern et al., 2023; Donlon et al., 2012). The OSTIA product provides an estimate of the foundation SST, which is the SST free of diurnal variability. Data were obtained from Marine Copernicus (https://data.marine.copernicus.eu/product/SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001/download?dataset=METOFFICE-GLO-SST-L4-NRT-OBS-SST-V2) with its product being Global Ocean Sea Surface Temperature and Sea Ice Analysis (SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001).

Wind data were obtained from the Copernicus Marine Service product Global Ocean Sea Surface Wind and Stress from Scatterometer and Model (WIND_GLO_PHY_L4_NRT_012_004). This Level-4 near-real-time product combines observations from Advanced Scatterometer (ASCAT) sensors onboard Metop-B and Metop-C satellites with collocated operational fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) to reduce systematic biases and improve surface wind estimation accuracy. The dataset provides global sea-surface wind information with a horizontal spatial resolution of 0.125° × 0.125° and an original temporal resolution of hourly observations.

To understand the vertical profile, we analyze potential seawater density, and this data is calculated from seawater potential temperature and seawater salinity. The Copernicus Marine Environment Monitoring Service (CMEMS) (GLOBAL_MULTIYEAR_PHY_001_030) provides the temperature and salinity data. Both data have a spatial resolution of 0.083º × 0.083º, and the value of RMSD reaches 0.4ºC (temperature) and 0.2 psu (salinity).

All remote sensing data were analyzed on a monthly climatology basis following (Fikra et al., 2025),

$$r = \frac{1}{n}\sum_{i=1}^{n} x_i(x, y, t)$$

Where X (x, y) is an average of the pixels data, xi(x, y, t) is the ith value of the data at position (x, y) and time (t). Furthermore, n is a number of data (i.e., from 2025 to 2025). xi is excluded from the calculation if that pixel has a missing data value.

The relationship between SST and wind speed is described in terms of the Pearson correlation (*r*). The correlation coefficients are calculated as follows (Zhu et al., 2021):

$$r = \frac{\sum(x_i - \bar{\bar{\bar{x}}})(y_i - \bar{\bar{\bar{y}}})}{\sqrt{\sum(x_i - \bar{\bar{\bar{x}}})^2 \sum(y_i - \bar{\bar{\bar{y}}})^2}}$$

where x and y are the chlorophyll-a and precipitation data, x and y are the average values, *n* is the number of matching chlorophyll-a and precipitation data. The Pearson correlation is used to describe the linear relationship between chlorophyll-a and precipitation data. After testing the hypothesis, the correlation coefficient is then interpreted to determine the strength of the correlation.

Table 1. Correlation strength categories (Prijana and Yanto, 2020)

Strength level	Categories
< 0.20	Slight (weak correlation)
0.20 -0.40	Low correlation
0.40 -0.70	Moderate correlation
0.70 -0.90	High correlation
0.90 -1.00	Very high correlation

RESULT AND DISCUSSION

The spatial distribution of SST data presented in Figure 2 indicates that the SST exhibits monthly fluctuations. The SST distribution exhibits clear seasonal variability throughout the year, with values ranging approximately between 25–30 °C. In general, warmer SST conditions dominated during January–May and October–December, whereas lower SST values were observed during June–September. During the first transitional period and west monsoon conditions (December–May), SST remained relatively high across most of the study area, with temperatures generally exceeding 29 °C. The warmest conditions occurred during March–May, when SST reached nearly 30 °C, particularly in the northern and central parts of the study area. The relatively homogeneous distribution of warm surface waters during this period indicates stable upper-ocean conditions with limited vertical mixing (Yu et al., 2025).

A significant SST decrease began during June and became more pronounced during July–September. The strongest cooling was observed in the southern offshore region, where SST locally decreased to approximately 25–26 °C. This cooling pattern indicates the occurrence of seasonal oceanographic processes capable of transporting colder subsurface waters toward the surface layer. This aligns with the attributes of Indonesian tropical waters, shaped by thermal interaction between the atmosphere and the ocean, including upwelling phenomena in deeper waters (Napitu et al., 2015; Habibullah and Tarya, 2021).

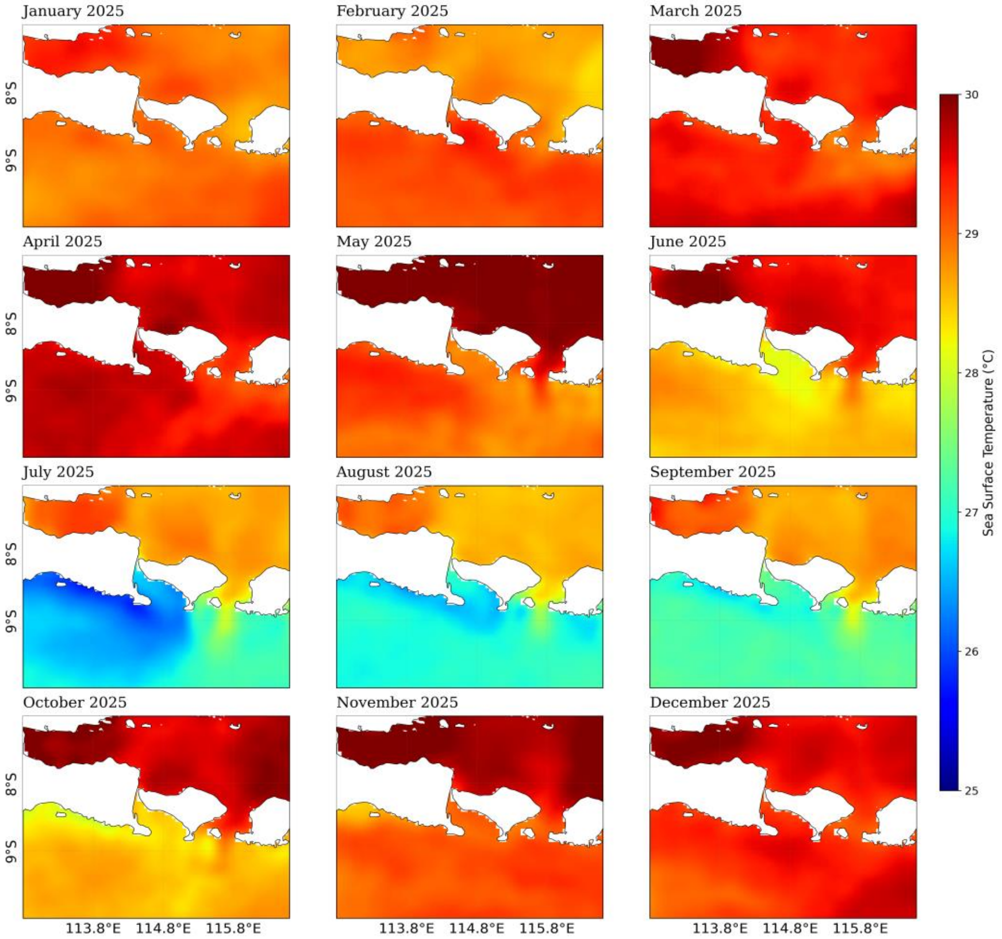

Figure 2. The spatial distribution of sea surface temperature in the waters of Banyuwangi Regency, East Java, Indonesia for 2025

To identify the possible mechanism responsible for the SST variability observed in Figure 2, surface wind conditions were analyzed and presented in Figure 3. The wind field demonstrates substantial seasonal changes in both speed and direction throughout 2025. During January–April, surface winds were relatively weak, generally below 4 m/s, and displayed predominantly zonal flow patterns. Under these conditions, atmospheric forcing over the ocean surface remained relatively weak, resulting in minimal vertical mixing and allowing surface waters to retain accumulated heat (Cui and Xu, 2024). Consequently, SST remained relatively high during this period.

In contrast, wind intensity increased substantially beginning in June and remained strong throughout July–September. Wind speeds during this period exceeded approximately 6–8 m/s over offshore regions south of Banyuwangi. The wind vectors also became more persistent, dominated by southeasterly flow associated with the southeast monsoon system. The strengthening of southeasterly winds likely enhanced momentum transfer between the atmosphere and ocean surface, thereby intensifying Ekman transport processes. In the Southern Hemisphere, southeasterly wind forcing generally induces offshore transport of surface waters, creating divergence near the coast and promoting upward movement of colder subsurface water masses (Setyohadi et al., 2021). Therefore, the SST cooling observed during June–September in Figure 2 is likely associated with seasonal wind-driven upwelling processes.

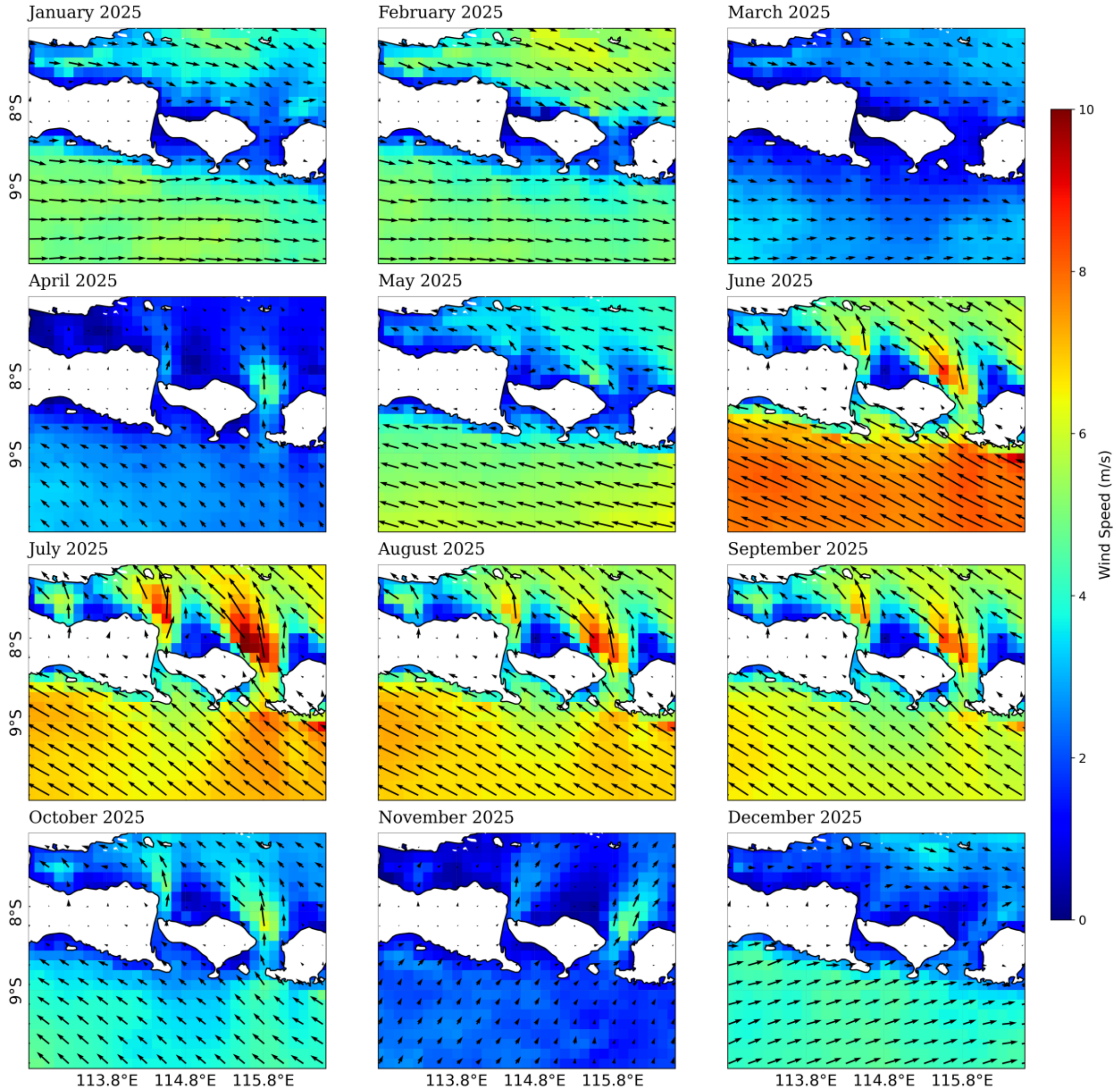

Figure 3. The spatial distribution of surface wind speed in the waters of Banyuwangi Regency, East Java, Indonesia for 2025

To further clarify the relationship between SST variability and wind forcing, Figure 4 presents the temporal variability of wind speed and SST together with the Hovmöller diagram of seawater density structure. The combined datasets reveal a consistent seasonal relationship between atmospheric forcing and upper-ocean conditions (Jo et al., 2024). The temporal graph shows that SST and wind speed exhibit an inverse relationship throughout the year. SST increased gradually from January and reached maximum values during March–April (~29.5–29.7 °C), when wind intensity weakened to below approximately 1.5–2 m/s. However, beginning in May–June, wind speed increased sharply and reached a peak of approximately 5.4 m/s during June, while SST simultaneously decreased rapidly. The lowest SST values occurred during July–September (~26–27 °C), coinciding with persistently strong wind conditions (~4–5 m/s). Following the weakening of winds during October–December, SST gradually increased again and exceeded 29 °C by the end of the year. This temporal pattern strongly suggests that wind variability plays an important role in regulating SST conditions in the study area.

The density structure shown in the Hovmöller diagram provides additional evidence supporting this mechanism. During January–April, the density contours remained relatively deep and stable, indicating stratified upper-ocean conditions with limited vertical displacement. The 23 kg m⁻³ isopycnal was generally located at depths of approximately 70–80 m, while the 25 kg m⁻³ contour occurred near 120–130 m depth. However, during June–September, both density contours shifted upward considerably. The 23 kg m⁻³ isopycnal shoaled to approximately 45–50 m depth, while the 25 kg m⁻³ contour also migrated upward. The upward displacement of isopycnals indicates intrusion of denser subsurface waters into shallower layers. This shoaling of density surfaces is physically consistent with the observed SST cooling. Colder waters possess higher density due to thermal contraction; therefore, the upward movement of denser waters strongly suggests that subsurface cold water masses reached the upper layer during the southeast monsoon period (Painter, 2020). The simultaneous occurrence of stronger winds, SST cooling, and upward displacement of density contours indicates a coherent response of the ocean system to seasonal atmospheric forcing.

Interestingly, the strongest density response occurred slightly after the peak wind intensity observed in June. Maximum shoaling of density contours became more pronounced during July–September, suggesting the existence of a temporal lag between atmospheric forcing and oceanic adjustment processes. Such delayed responses are commonly observed in tropical upwelling systems, where ocean stratification requires time to fully respond to sustained wind forcing.

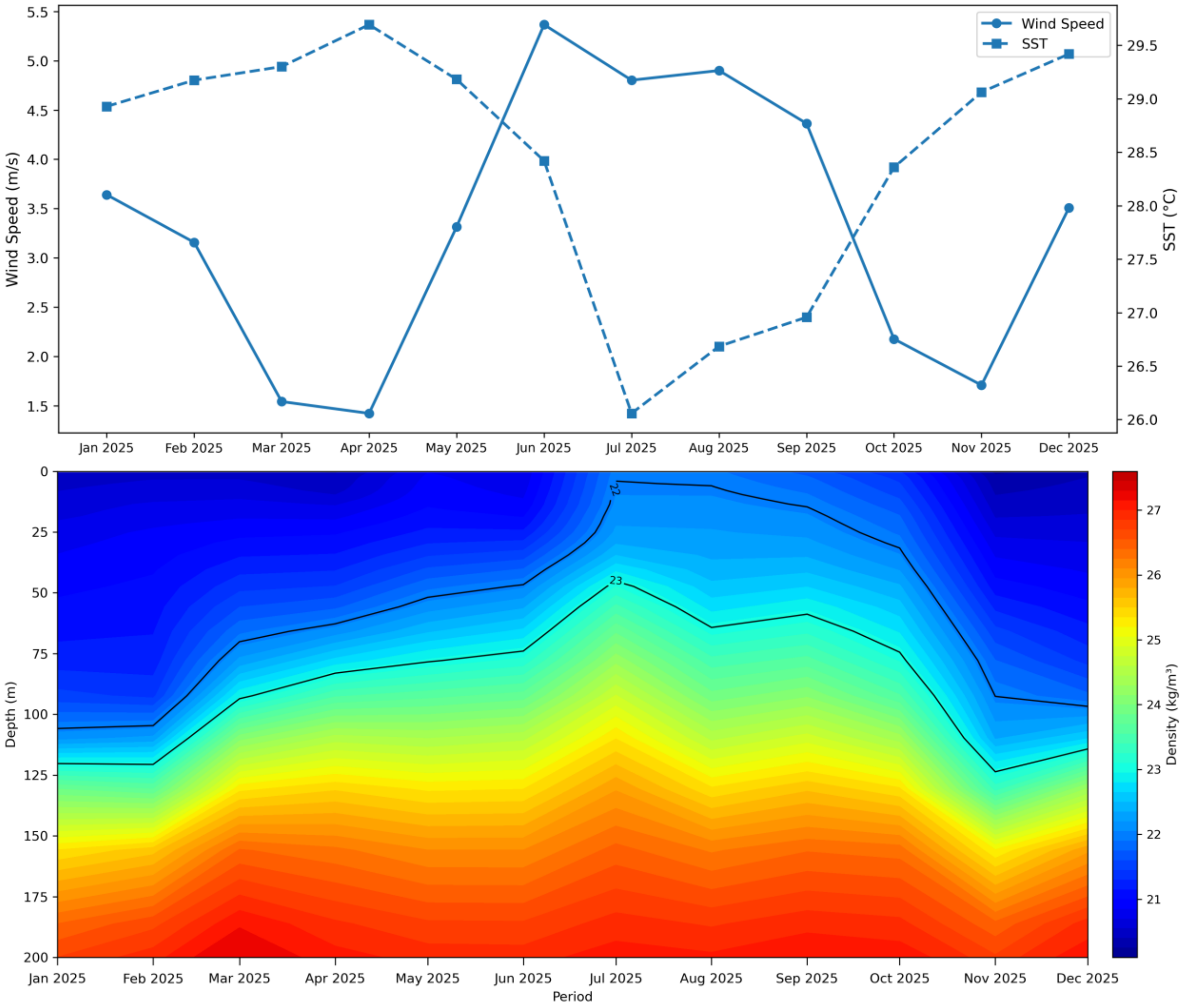

Figure 4. Time series of monthly wind speed and SST variability (upper panel) and Hovmöller diagram of seawater density structure (lower panel) in the southern Banyuwangi waters during 2025

To quantitatively evaluate the relationship between wind variability and SST, Pearson correlation analysis was performed between monthly wind speed and SST values. The analysis produced a correlation coefficient of **r = −0.68**, indicating a moderately strong negative relationship between the two variables. This negative correlation quantitatively confirms the inverse relationship observed in both spatial and temporal analyses. The correlation result indicates that increasing wind intensity tends to be followed by decreasing SST conditions. Stronger winds enhance surface mixing and Ekman-driven upwelling processes, allowing colder subsurface waters to reach the surface layer and reduce SST. Conversely, weaker winds reduce vertical exchange and favor heat accumulation in the upper ocean, resulting in warmer SST conditions (Shields et al., 2024). Although the correlation coefficient does not indicate a perfect relationship, the relatively strong negative value suggests that wind forcing is a major factor controlling

SST variability in southern Banyuwangi waters during 2025. Other factors, such as surface heat fluxes, ocean circulation, mesoscale processes, and atmospheric variability, may also contribute to SST fluctuations.

Overall, the integrated analysis of SST distribution, wind variability, density structure, and statistical correlation demonstrates that seasonal monsoon-driven wind forcing plays a dominant role in controlling upper-ocean variability in southern Banyuwangi waters. Intensification of southeast monsoon winds during June–September enhances upwelling processes, resulting in colder and denser surface waters, whereas weaker wind conditions during the transition and northwest monsoon periods favor warmer and more stratified upper-ocean conditions.

CONCLUSION

The present study demonstrates that Sea Surface Temperature (SST) variability in the waters of Banyuwangi during 2025 exhibited a clear seasonal pattern strongly associated with surface wind variability and changes in water-column density structure. SST remained relatively high during January–May and October–December, generally exceeding 29 °C, whereas significant cooling occurred during June–September, with temperatures decreasing to approximately 26–27 °C. This cooling period coincided with an increase in wind intensity during the southeast monsoon season, when wind speeds reached approximately 5–6 m/s suggesting stronger atmospheric forcing over the ocean surface. Enhanced wind conditions likely intensified Ekman transport processes and promoted upward movement of colder subsurface waters. This mechanism was further supported by the Hovmöller density structure, which showed upward displacement of isopycnal layers during June–September, indicating shoaling of denser water masses toward shallower depths. In addition, Pearson correlation analysis revealed a moderately strong negative relationship ($r = -0.68$) between wind speed and SST, confirming that increased wind intensity was generally associated with lower SST conditions. Overall, the integrated analysis of SST, wind variability, density structure, and statistical relationships indicates that monsoon-driven wind forcing plays a dominant role in controlling seasonal oceanographic variability in the waters of Banyuwangi through wind-induced vertical processes.

REFERENCES

deCastro, M., M.Gómez-Gesteira, X.Costoya, and F.Santos. 2014. Upwelling influence on the number of extreme hot SST days along the Canary upwelling ecosystem. *J. Geophys. Res. Oceans*, 119, 3029–3040, https://doi.org/10.1002/2013JC009745.

Cui, C., & Xu, L. 2024. The Mesoscale SST–Wind Coupling Characteristics in the Yellow Sea and East China Sea Based on Satellite Data and Their Feedback Effects on the Ocean. *Journal of Marine Science and Engineering*, *12*(10), 1743. https://doi.org/10.3390/jmse12101743.

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E. & Wimmer, W. (2012). The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system. *Remote Sensing of Environment,* 116: 140-158. https://doi.org/10.1016/j.rse.2010.10.017.

Fikra, H., Wijaya, Y. J., Kunarso & Wisha, U. J. (2025). Studi Variabilitas Upwelling Berdasarkan Data Angin, Suhu Permukaan Laut, Dan Klorofil-A Di Laut Flores. *Indonesian Journal of Oceanography*, 7(3): 265-274. https://doi.org/10.14710/ijoce.v7i3.27907.

Good, S., Fiedler, E., Mao, C., Martin, M. J., Maycock, A., Reid, R., Roberts-Jones, J., Searle, T., Waters, J., While, J., & Worsfold, M. (2020). The Current Configuration of the OSTIA System for Operational Production of Foundation Sea Surface Temperature and Ice Concentration Analyses. *Remote Sensing*, 12(4), 720. https://doi.org/10.3390/rs12040720.

Habibullah, A. D. & Tarya, A. (2021). Sea surface temperature variability in Indonesia and its relation to regional climate indices. IOP Conference Series: Earth and Environmental Science, Volume 925, The 3rd International Conference on Maritime Sciences and Advanced Technology 5-6 August 2021, Pangandaran, Indonesia (Virtual). https://doi.org/10.1088/1755-1315/925/1/012008?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle.

Horii, T., I.Ueki, F.Syamsudin, I.Sofian, and K.Ando. 2016. Intraseasonal coastal upwelling signal along the southern coast of Java observed using Indonesian tidal station data. *J. Geophys. Res. Oceans*, 121, 2690–2708. https://doi.org/10.1002/2015JC010886.

Jo, A. R., Lee, J.-Y., Sharma, S., & Lee, S.-S. 2024. Season-dependent atmosphere-ocean coupled processes driving SST seasonality changes in a warmer climate. *Geophysical Research Letters*, 51, e2023GL106953. https://doi.org/10.1029/2023GL106953.

Kramer, S. M. & Karnauskas, K. B. 2025. Air-sea interactions over persistent warm midlatitude SST anomalies. *Climate Dynamics,* 63, 281. https://doi.org/10.1007/s00382-025-07771-z.

Martono. 2016. Seasonal and Inter Annual Variation of Sea Surface Temperature in the Indonesian Waters. *Forum Geografi,* 30(2): 120. https://doi.org/10.23917/forgeo.v30i2.1530.

Napitu, A. M., Gordon, A. L. & Pujiana, K. (2015). Intraseasonal Sea Surface Temperature Variability across the Indonesian Seas. *Journal of Climate,* 28(2): 8710–8727. https://doi.org/10.1175/JCLI-D-14-00758.1.

Painter, S. C. 2020. The biogeochemistry and oceanography of the East African Coastal Current. *Progress in Oceanography,* 186, 102374. https://doi.org/10.1016/j.pocean.2020.102374.

Prijana, & Yanto, A. (2020). Metode penelitian perpustakaan dan sains informasi. Bandung, Indonesia: Simbiosa Rekatama Media.

Rachman, H. A., Setiawati, M. D., Hidayah, Z., Syah, A. F., Nandika, M. R., Lumban-Gaol, J., As-syakur, A. R. & Syamsudin, F. 2024. Dynamic of upwelling variability in southern Indonesia region revealed from satellite data: Role of ENSO and IOD. *Journal of Sea Research,* 202: 102543. https://doi.org/10.1016/j.seares.2024.102543.

Redfern, S., Optis, M., Xia, G. & Draxl, C. (2023). Offshore wind energy forecasting sensitivity to sea surface temperature input in the Mid-Atlantic. *Wind Energy Science,* 8(1): 1-23. https://doi.org/10.5194/wes-8-1-2023.

Setyohadi, D., Zakiyah, U., Sambah, A. B., & Wijaya, A. 2021. Upwelling Impact on *Sardinella lemuru* during the Indian Ocean Dipole in the Bali Strait, Indonesia. *Fishes*, *6*(1), 8. https://doi.org/10.3390/fishes6010008.

Simanjuntak, F., & Lin, T. H. 2022. Monsoon Effects on Chlorophyll-a, Sea Surface Temperature, and Ekman Dynamics Variability along the Southern Coast of Lesser Sunda Islands and Its Relation to ENSO and IOD Based on Satellite Observations. *Remote Sensing*, 14(7), 1682. https://doi.org/10.3390/rs14071682.

Shields, C.A., Li, H., Castruccio, F.S., Fu, D., Nardi, K., Liu, X. & Zarzycki, C. 2024.. Response of the upper ocean to northeast Pacific atmospheric rivers under climate change. *Commun Earth Environ* **5**, 603. https://doi.org/10.1038/s43247-024-01774-0.

Tang, C., Hao, D., Wei, Y., Zhao, F., Lin, H., & Wu, X. (2022). Analysis of Influencing Factors of SST in Tropical West Indian Ocean Based on COBE Satellite Data. *Journal of Marine Science and Engineering*, *10*(8), 1057. https://doi.org/10.3390/jmse10081057.

Yu, X., Yi, D. L., & Wang, P. 2025. Enhancing Ocean Temperature and Salinity Reconstruction with Deep Learning: The Role of Surface Waves. *Journal of Marine Science and Engineering*, *13*(5), 910. https://doi.org/10.3390/jmse13050910.

Zhu, D., Ilyas, A. M., Wang, G. & Zeng, B. (2021). Long-term hydrological assessment of remote sensing precipitation from multiple sources over the lower Yangtze River basin, China. Meteorological Applications, 28(3): e1991. https://doi.org/10.1002/met.1991.