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Examination of Wind's Effect on Sea Surface Temperature Variability in Banggai Regency Waters, Central Sulawesi, Indonesia

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A B S T R A C T :

Banggai Regency waters in Central Sulawesi are an important marine ecosystem within the Coral Triangle. Sea Surface Temperature (SST) is a key parameter that influences ecosystem health; however, the interaction of global and local factors affects its variability. This study aims to analyze the spatial and temporal patterns of SST and surface wind in Banggai waters throughout 2024 and examine their physical relationship. Level-4 SST data from the Operational Sea Surface Temperature and Ice Analysis (OSTIA) with a resolution of 0.05° and wind data from the Cross-Calibrated Multi-Platform (CCMP) with a resolution of 0.25° were analyzed statistically and descriptively. The results showed that monthly SST fluctuated between 27.0°C and 31.0°C, with different spatial distribution patterns based on depth and season. Wind speed exhibits a seasonal pattern that is counter-phase with SST, with the highest winds (8-9 m/s) occurring during the East Monsoon (June-August) and the lowest winds (4-6 m/s) during the West Monsoon (December-February). Correlation analysis reveals a strong negative relationship between wind and SST, particularly in southern waters (-0.81), compared to a moderate correlation at northern waters (-0.61). The underlying physical mechanisms for this relationship are increased latent heat flux and wind-driven upwelling during the East Monsoon, which cool the sea surface. This study concludes that seasonal wind variability is a major local driver of SST patterns in the waters of the Banggai Islands. These findings highlight the dominant role of seasonal monsoon winds in driving SST variability in Banggai waters and provide scientific insight for improving marine resource management under changing climate conditions.

Keywords: Sea Surface Temperature, Wind, Banggai Regency, Monsoon, Upwelling

1. Introduction

The waters of Banggai Regency, located in Central Sulawesi, Indonesia, constitute a crucial marine ecoregion within the Coral Triangle and are renowned for their prolific biodiversity (Allen, 2007; Moore and Ndobe, 2013). Oceanographic conditions in this region are generally influenced by complex interactions between global and regional climate phenomena. Sea surface temperature (SST) is a key factor that directly affects the health of coral reefs, the distribution of species, the productivity of phytoplankton, and, in the end, the long-term health of fish stocks (Hoegh-Guldberg & Bruno, 2010). Variability in SST across Indonesian seas is strongly influenced by both large-scale climate modes and seasonal wind forcing. At the global scale, phenomena such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are well-known drivers of SST anomalies in the region (Saji et al., 1999; Susanto et al., 2001; Rachman et al., 2024). Regionally, the Indonesian monsoon system generates seasonal wind reversals associated with the Asian–Australian climate circulation, which modulate heat exchange and surface ocean dynamics throughout the year. At local and meso-scale levels, wind remains the dominant mechanical driver affecting SST. Wind patterns and intensities influence SST through several main mechanisms: (1) strong winds increase the latent heat flux from the atmosphere to the ocean, thereby cooling the ocean surface (Fairall et al., 2003); (2) wind stress increases turbulence and mixing of the warm surface layer with cooler water from the underlying layers (Kawai & Wada, 2007); (3) surface winds are the main driver of ocean currents to distribute SST horizontally. When winds blow parallel to the coastline, they can induce upwelling or downwelling, which significantly alters the spatial distribution of SST (Wyrtki, 1961).

While monsoon-related SST dynamics have been documented in other Indonesian regions such as the Bali Strait, southern Java, and the Flores Sea, scientific understanding of similar processes in Banggai waters remains limited. The unique characteristics of this area, its archipelagic configuration, irregular bathymetry, and exposure to seasonal monsoon forcing suggest that SST responses to wind may differ from surrounding regions (Hamzah et al., 2024). These conditions may generate localized wind patterns and distinctive thermal structures within the Banggai archipelago. Previous studies have largely focused on SST variability or ecosystem responses, leaving a gap in understanding the physical coupling between SST and wind specifically in this region. Therefore, this study aims to analyze the spatial and temporal patterns of SST and surface wind variability in the waters of Banggai Regency and to examine the dynamic relationship between these two parameters. The results are expected to contribute to a broader understanding of physical oceanography in the eastern Indonesian seas and provide a scientific basis for marine and fisheries management in Banggai Regency, particularly in anticipating the impacts of climate variability and climate change.

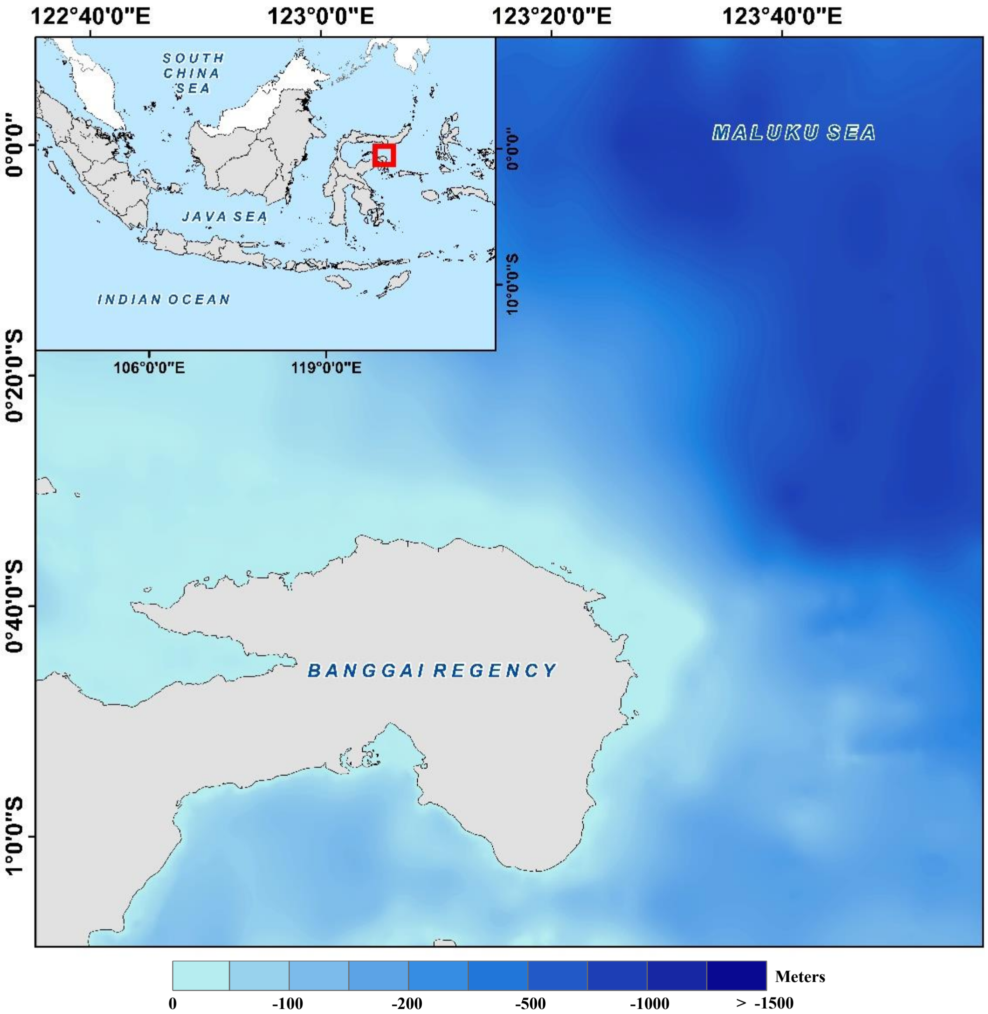

Figure 1. Map of the study area showing the geographic setting and bathymetry of Banggai Waters, Central Sulawesi, Indonesia

2. Methodology

Sea Surface Temperature (SST) data were obtained from the Operational Sea Surface Temperature and Ice Analysis (OSTIA) product, which provides Level-4 foundation SST with a spatial resolution of 0.05° x 0.05°. The dataset is generated through data assimilation that integrates satellite observations with in-situ measurements from buoys and ships (Good et al., 2020; Redfern et al., 2023; Donlon et al., 2012). OSTIA offers SST fields that are free from diurnal variability, making them suitable for analyzing large-scale thermal patterns. 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). The OSTIA data used has a Root Mean Square Error value of around 0.34. Surface wind data were sourced from the Cross-Calibrated Multi-Platform (CCMP) dataset produced by Remote Sensing Systems (http://remss.com/). This dataset combines data from satellites, moored buoys, and numerical models, with accuracy reflected in the Root Mean Square Error (RMSE) of approximately 1 m/s (Li et al., 2021). CCMP has a spatial resolution of 0.25° x 0.25° and is updated four times a day (every quarter-day).

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 2020 to 2023). xi is excluded from the calculation if that pixel has a missing data value.

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

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

where x_i represents SST values, y_i represents wind speed values, and $\bar{X}$ and $\bar{Y}$ are their respective monthly means. The Pearson coefficient was used to

quantify the linear relationship between seasonal SST and surface wind variability.
The correlation strength was interpreted based on Prijana & Yanto (2020), as shown in Table 1.

Table 1. Interpretation of Pearson correlation strength

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

3. Result and Discussion

Spatial distribution of SST in 2024 (Figure 2) shows a distinct seasonal pattern across Banggai Waters, with temperatures ranging from 27°C to 31°C. Warmer SST occurs from January to May, reaching its peak around April–May during the northwest monsoon. Weak winds and strong atmospheric heating contribute to the enhanced stratification and elevated surface temperatures during this period. From June to October, SST decreases in several areas, especially over deeper waters (>600 m), where temperatures fall to 27–28°C. Meanwhile, shallow coastal areas (<200 m) retain higher values (>30°C). This spatial contrast is typical of Indonesian archipelagic seas, where bathymetric variation strongly influences vertical mixing and the distribution of heat (Napitu et al., 2015; Habibullah & Tarya, 2021). This explanation aligns with the broader context of the study, which links SST variability to monsoon-driven wind patterns and local bathymetry, emphasizing the importance of physical oceanographic processes in shaping thermal structures in the Banggai region.

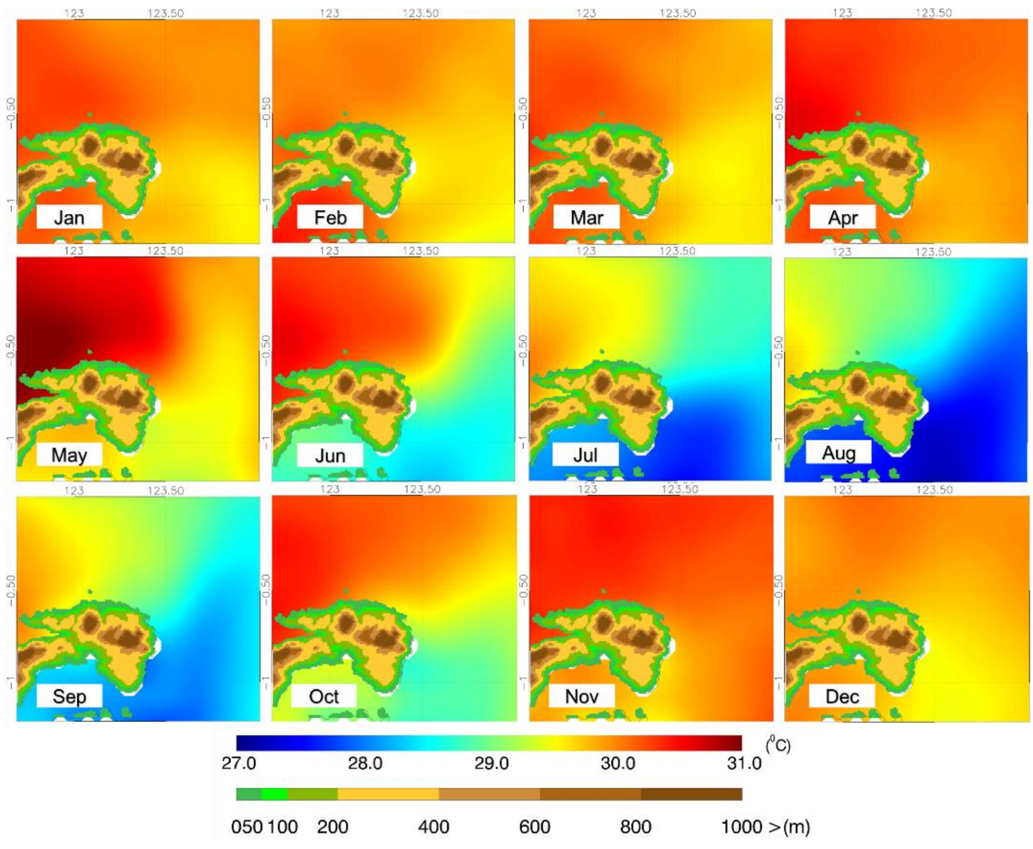

Figure 2. Spatial distribution of sea surface temperature in Banggai Waters in 2024

Surface wind patterns in 2024 (Figure 3) also show strong monsoonal characteristics. The wind speed data demonstrates an inverse correlation with the pattern of sea surface temperatures. Peak wind velocities occur from June to August (east monsoon), attaining 8-9 m/s; however, from December to February (west monsoon), wind velocities are comparatively diminished (4-6 m/s). This pattern signifies the influence of the Asian-Australian monsoon on regional ocean dynamics. During periods of vigorous southeasterly winds (June-August), upwelling occurs, bringing colder subsurface waters to the surface and consequently reducing sea surface temperature (SST) in several areas (Siswanto et al., 2021). Conversely, during the predominance of westerly winds (December-February), downwelling and sea surface warming escalate, resulting in elevated SST values. The physical mechanisms connecting wind and sea surface temperature (SST) can be elucidated through two primary processes: surface heat flux and upwelling. Intense winds enhance evaporation and surface turbulence, hence augmenting the transfer of heat from the ocean to the atmosphere (Klein et al., 1995; Kim & Lee, 2021). Moreover, winds that flow parallel to the shoreline can induce upwelling, transporting colder saltwater from the depths to the surface (Jury, 2024; Chen et al., 2024).

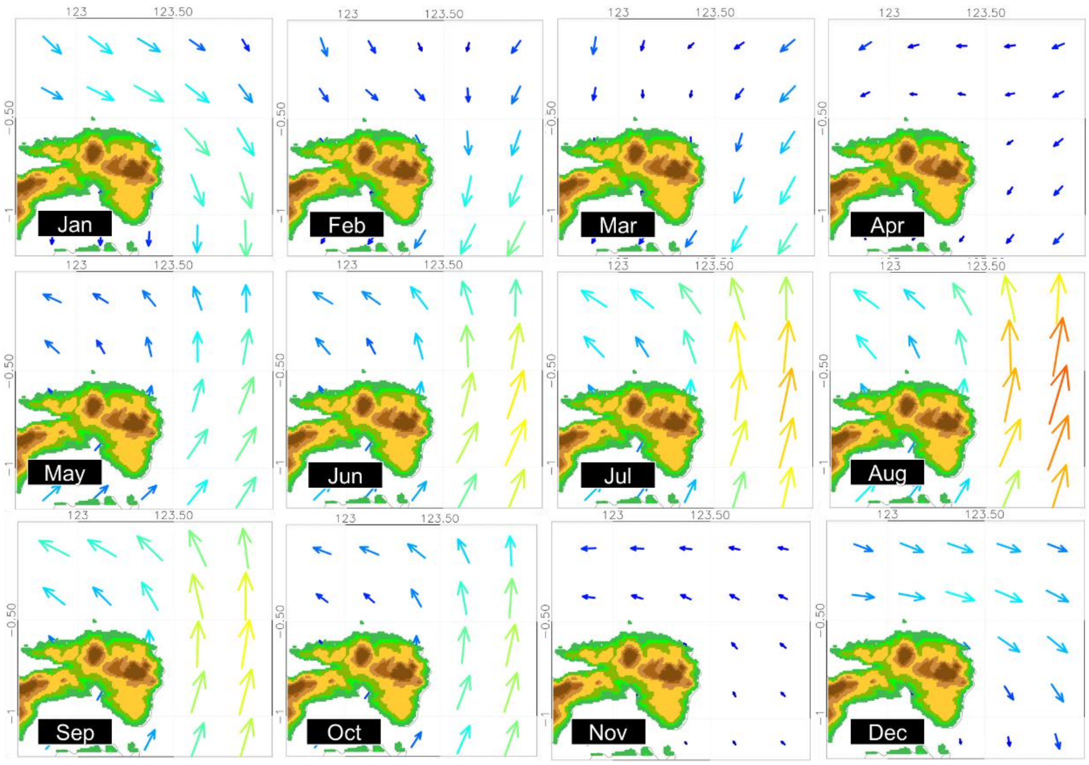

Figure 3. Spatial distribution of surface wind in Banggai Waters in 2024

To better understand the SST-wind interaction, monthly time-series data were extracted from two spatial subregions: northern waters (123.25° to 123.50° E; -0.25° to -0.50° S) and southern waters (123.50° to 123.75° E; -0.50° to -0.75° S). The extraction results are shown in Figure 4. Both regions exhibit clear seasonal signatures, where SST declines as wind speed increases. However, the southern waters, which experience stronger southeasterly winds (6–9 m/s), show a more pronounced cooling response. Meanwhile, the northern waters, with relatively weaker winds (2–4 m/s), show milder fluctuations in SST. The stronger southeasterly flow observed in the southern subregion is consistent with the regional influence of the southeast monsoon. As wind intensity increased, SST decreased more markedly, with the northern waters cooling to approximately 29°C and the southern waters reaching around 28°C. These stronger winds not only carried drier air masses but also enhanced vertical mixing and upwelling in the southern part of the region, a pattern commonly reported in Indonesian waters (Setyohadi et al., 2021).

To quantify the relationship between the two parameters, a Pearson correlation analysis was performed. The northern waters showed a moderate negative correlation ($r = -0.61$), while the southern waters exhibited a strong negative correlation ($r = -0.81$). The negative correlation values indicate that wind speed and SST vary in opposite phases, with higher wind speeds associated with lower SST, confirming the physical mechanisms previously discussed (Burgund et al., 2023). The interaction between wind and sea surface temperature (SST) in Banggai Regency waters demonstrates a significant influence of monsoonal wind patterns on local oceanographic conditions. Seasonal strengthening of southeasterly winds during the Southeast Monsoon enhances latent heat flux and surface evaporation, leading to substantial cooling of the sea surface (Fairall et al., 2003). In addition, intensified winds promote vertical mixing and upwelling, particularly in regions with open exposure to monsoonal flow, as commonly observed across the Indonesian seas (Wyrtki, 1961; Susanto et al., 2001). This dynamic is evident in the spatial heterogeneity of SST, where deeper waters experience greater temperature reductions compared to shallower coastal zones. The strong negative correlation between wind speed and SST, especially in the southern subregion of Banggai Waters, underscores the role of wind-driven mixing and cold-water uplift in modulating thermal structures. These findings highlight the critical importance of considering local wind regimes and bathymetric features in understanding SST variability, which has direct implications for marine ecosystem health and resource management under evolving climate conditions.

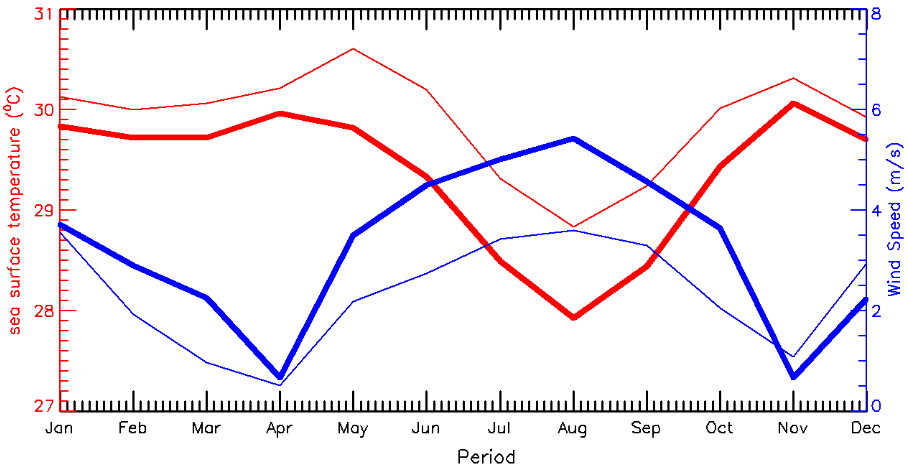

Figure 4. Monthly time series of sea surface temperature (red) and surface wind speed (blue) for the northern (thin lines) and southern (thick lines) waters of Banggai in 2024

4. Conclusion

Wind speeds peak between June and August in both regions, with the northern waters experiencing weaker winds (approximately 2–4 m/s) and the southern waters experiencing stronger winds (around 6–9 m/s). This pattern corresponds to the active phase of the southeast monsoon blowing from the Australian continent toward Asia. As wind intensity increases, SST values decrease, with the northern waters cooling to around 29°C and the southern waters reaching approximately 28°C. The correlation between wind and SST in the northern waters is –0.61, indicating a moderate negative relationship, while the southern waters show a stronger negative correlation of –0.81. A negative correlation indicates that these variables exhibit opposite phases, as discussed previously. Overall, the spatial and temporal analysis of SST and wind demonstrates a strong inverse relationship driven by the Asian-Australian monsoon cycle. These results align with established ocean-atmosphere interaction theory in tropical regions, where wind plays a major role in SST variability through heat exchange, vertical mixing, and upwelling processes.

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