Diurnal Cycle of Land–Sea Breeze and Coastal Abrasion in Bengkulu Region

Siti Hairunnisa Norfahmi[1]*, Lizalidiawati[1], Riska Ekawita[1] , M. Fikri Azhari[1] , Maura Alyafie Nurel[1], Putri Lisya Anggraini[1], Siti Chusnul Chatimah Nurahmah[2]

[1]Faculty of Mathematics and Natural Sciences, Bengkulu University
Jl. W.R. Supratman, Kandang Limun, Bengkulu Indonesia
[2]Faculty of Geological Engineering, Padjadjaran University
Jl. Dipati Ukur No. 35, Bandung, Jawa BaratIndonesia.
Email: shnorfahmi@unib.ac.id

Abstract

This study examines the diurnal cycle of land–sea breeze and its association with micro-scale coastal abrasion along the Bengkulu coast from 2020 to 2025. Hourly wind data were analyzed to characterize the zonal and meridional components, as well as divergence patterns, revealing persistent diurnal wind reversals and spatially coherent circulation features. Concurrently, shoreline change was quantified across 163 transects using the Linear Regression Rate (LRR), End Point Rate (EPR), Net Shoreline Movement (NSM), and Weighted Shoreline Evolution (WSE) metrics, identifying locations prone to abrasion and accretion. The results show shoreline change analysis in the Digital Shoreline Analysis System (DSAS) identifies localized segments (transects 41–44) with significant negative rates, indicating persistent abrasion. Atmospheric analysis reveals a robust diurnal cycle, with nighttime land-breeze divergence over coastal land and convergence offshore, reversed during the daytime by sea-breeze convergence over land and offshore divergence. This cycle persists year-round, while seasonal monsoon winds modulate zonal and meridional components. The spatial correspondence between high abrasion zones and strong diurnal wind convergence suggests a potential physical linkage whereby repeated atmospheric forcing may influence nearshore wave energy and sediment transport. Integrating DSAS-derived shoreline trends with diurnal circulation analysis provides a physically grounded framework for assessing coastal vulnerability and informing management strategies in tropical coastal environments.

Keywords : diurnal cycle, land–sea breeze, coastal abrasion, shoreline change, Bengkulu

INTRODUCTION

Indonesia's geographical setting as a vast tropical archipelago exerts a strong control on its weather, climate, and coastal dynamics. The interaction between land and ocean across thousands of kilometers of coastline makes coastal regions particularly vulnerable to shoreline change processes, including abrasion and accretion. While these processes are naturally occurring, their intensity and spatial manifestation vary significantly from one coastal segment to another, emphasizing the importance of understanding local atmospheric and oceanographic conditions in explaining observed shoreline changes.

Previous studies have consistently identified ocean waves as a primary driver of coastal abrasion, whether generated by seasonal atmospheric circulation such as the Asian–Australian monsoon or by large-scale climate variability including the El Niño–Southern Oscillation (ENSO) (Barnard *et al.,* 2015, 2017; Purwanto *et al.,* 2021). These large-scale forcings influence wave energy, direction, and persistence, thereby controlling sediment transport along the coast. Because wave conditions are ultimately influenced by atmospheric forcing, variations in local wind patterns can also modify surface wind stress, nearshore wave activity, and sediment transport pathways on daily timescales, thereby contributing to spatial differences in coastal response. However, beyond these synoptic and seasonal processes, several studies have highlighted the role of local atmospheric phenomena in modulating nearshore hydrodynamics. In particular, land–sea breeze circulation has been shown to affect coastal wind stress, wave generation, and nearshore current patterns, potentially accelerating erosion or promoting sediment redistribution at shorter temporal and spatial scales (Pattiaratchi *et al.,* 1993; Torres-Freyermuth, 2017).

Along the Bengkulu coast on the western margin of Sumatra, coastal abrasion has emerged as a critical environmental and socio-economic

*Corresponding author
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issue. This region is directly exposed to the Indian Ocean, making it highly sensitive to wind–wave interactions. Previous investigations have reported that strong winds and high wave energy significantly contribute to shoreline retreat in Bengkulu (Hasanudin and Kusmanto, 2021; Lubis *et al.,* 2020; Rahmawati *et al.,* 2024; Sugianto *et al.,* 2022; Yarmanto *et al.,* 2025). Observational records from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) indicate that significant wave heights in southern Bengkulu waters can reach up to 2.9 m, accompanied by wind speeds exceeding 25 knots, conditions that intensify coastal abrasion processes (BMKG, 2025). These physical impacts have translated into tangible land loss, with reported shoreline retreat of up to two meters per year in several coastal sectors (Putra *et al.,* 2025), threatening infrastructure, tourism areas, and local livelihoods.

Although large-scale drivers of coastal abrasion, such as seasonal monsoons and ENSO-related wave variability, are relatively well understood, the potential role of local diurnal atmospheric phenomena, particularly land–sea breeze circulation, remains largely unexplored in tropical coastal regions like Bengkulu. While previous studies have suggested that diurnal wind patterns may affect nearshore hydrodynamics, their actual contribution to shoreline change at specific locations has yet to be clearly quantified.

The primary aim of this study is therefore to document and characterize the diurnal cycle of land–sea breeze along the Bengkulu coast and to describe patterns of micro-scale shoreline change from 2020 to 2025 using satellite-derived metrics through the Digital Shoreline Analysis System (DSAS). By providing a detailed observational record of both atmospheric circulation and coastal change, this research establishes a baseline for future investigations into potential interactions, while also contributing valuable information for coastal monitoring and management in a region vulnerable to erosion and land loss.

MATERIALS AND METHODS

This study utilizes the ERA5 monthly averaged reanalysis by hour of day dataset on pressure levels obtained from the Copernicus Climate Data Store (CDS) for atmospheric circulation. The dataset provides global coverage with a horizontal resolution of 0.25° × 0.25°. Near-surface wind conditions were represented by the divergence (d), the zonal (u), and meridional (v) wind components at the 1000 hPa pressure level, which together provide a comprehensive characterization of near-surface wind circulation along the Bengkulu coast. These parameters were selected to capture both the directional components of the wind field and the convergence–divergence patterns associated with land–sea breeze dynamics. All hourly fields were converted from Coordinated Universal Time (UTC) to Western Indonesian Time (WIB; UTC+7) prior to analysis. Climatological diurnal wind fields were constructed by averaging monthly mean hourly data over the period September 2020–August 2025. Seasonal composites (DJF, MAM, JJA, and SON) were derived from the same five-year climatological record.

For shoreline analysis, we employed Sentinel-2 Level-2A (L2A) imagery, which requires no additional atmospheric correction, streamlining the preprocessing workflow. Bands 3 (Green, 10 m) and 8 (Near-Infrared, 10 m) were used to derive the Normalized Difference Water Index (NDWI) following McFeeters (1996). NDWI enhances water features by exploiting the higher reflectance of water in the green band and its strong absorption in the near-infrared band, while suppressing vegetation and soil signals.

Shoreline change was quantified along 163 transects using multiple Digital Shoreline Analysis System (DSAS) metrics: Net Shoreline Movement (NSM), End Point Rate (EPR), Linear Regression Rate (LRR), and Weighted Shoreline Evolution (WSE). NSM measures the total displacement of the shoreline between the earliest and latest positions along each transect, with positive values indicating seaward advance and negative values indicating landward retreat. EPR quantifies the average annual rate of change based on NSM and the time interval, expressed in meters per year (m/yr), reflecting the overall speed of shoreline advance or erosion. LRR is derived from a least-squares linear regression of all shoreline positions over time. Unlike EPR, which only considers the first and last positions, LRR incorporates the full temporal dataset, providing a statistically robust estimate of long-term shoreline change rates, where the slope of the regression line represents the rate of shoreline movement. WSE assesses the variability of shoreline positions around the weighted regression line; in this approach, individual shoreline positions are assigned weights based on positional accuracy or other relevant

criteria. A smaller WSE indicates close adherence to the regression trend, while a larger WSE reflects greater variability or uncertainty in the dataset.

RESULT AND DISCUSSION

Figure 1 illustrates the climatological diurnal evolution of the divergence field together with the zonal and meridional wind components along the Bengkulu coastal region for the 5 years period. The observed patterns represent a direct atmospheric response to the thermal contrast between land and ocean surfaces. Owing to its lower heat capacity, the land surface warms and cools more rapidly than the adjacent ocean, producing a pronounced diurnal temperature gradient. This differential heating and cooling acts as the primary forcing mechanism for the land–sea breeze circulation and gives rise to the recurring daily cycles of low-level convergence and divergence observed in the coastal atmosphere (Atkinson, 1981; Miller *et al.,* 2003).

The division between the nighttime–morning phase (21:00–09:00 WIB) and the daytime–evening phase (09:00–21:00 WIB) is based on the climatological reversal of the wind vectors and divergence patterns observed in Figures 1–5, which indicate a transition from offshore-directed land-breeze circulation to onshore-directed sea-breeze circulation near 09:00 WIB and the opposite transition near 21:00 WIB.During the nighttime to early morning hours (approximately 21:00–09:00 local time), the land areas along the Bengkulu coast and the broader western coastline of Sumatra cool more rapidly than the nearby waters of the Indian Ocean. The resulting cooler, denser, and more stable air mass over land promotes subsidence. This downward motion generates horizontal outflow from the land toward surrounding regions, which is manifested as positive divergence anomalies over the coastal land area. At the same time, offshore-directed flow associated with the land breeze transports air toward the sea, leading to an accumulation of air mass over the nearshore marine environment. This accumulation is reflected in negative divergence anomalies over coastal waters, a canonical feature of nocturnal land-breeze circulation in tropical coastal regions (Crosman and Horel, 2010). Beyond the immediate land–sea interface, part of the air mass diverging from the coastal zone subsequently converges over the interior of Sumatra. This secondary convergence explains the presence of negative divergence values over inland regions during the same nighttime to morning period, occurring after the peak in coastal divergence.

Similar inland convergence following coastal divergence has been documented over the Maritime Continent and other tropical islands and is often attributed to mesoscale pressure adjustments, gravity-wave responses, and interactions with island-scale topography (Qian *et al.,* 2010; Vincent and Lane, 2017; Yang and Slingo, 2001). As a result, a coupled spatial pattern develops during the night–morning phase, characterized by divergence over coastal land, convergence over adjacent marine areas, and renewed convergence farther inland.

A reversal of the circulation occurs during the daytime to evening period (approximately 09:00–21:00 local time). Enhanced solar radiation heats the land surface more rapidly and to a greater extent than the ocean, causing the near-surface air over land to become warmer, less dense, and increasingly unstable. These conditions favor upward motion and the development of low-level convergence, which appears as negative divergence anomalies over the coastal land areas of Bengkulu and along the western coast of Sumatra. To compensate for rising air over land, air flows onshore from the sea, forming the sea-breeze circulation. Consequently, the nearshore marine region becomes a source of airflow and exhibits positive divergence anomalies during the daytime, consistent with both observational and modeling studies of tropical sea-breeze systems (Miller *et al*., 2003; Steele *et al*., 2015). The climatological divergence field ranges from values lower than -5×10^{-5} s^{-1} in convergence-dominated regions to values exceeding $+5 \times 10^{-5}$ s^{-1} in divergence-dominated areas, indicating that the observed land–sea breeze circulation is associated with a well-defined and dynamically significant low-level convergence–divergence structure. The contrasting patterns between the night–morning and day–evening periods provide clear evidence of a well-developed and organized diurnal circulation system in the Bengkulu coastal region. The persistence of these features throughout the five-year climatological record indicates that the land–sea breeze is not a sporadic or short-lived phenomenon but rather a stable and recurrent atmospheric process. Similar persistence of diurnal coastal circulation has been reported across the Indonesian Maritime Continent using long-term reanalysis and observational datasets (Szkolka *et al.,* 2023; Qian, 2008; Vincent and Lane, 2017).

Furthermore, the elongated spatial structure of the divergence and wind fields along the western coast of Sumatra suggests that the circulation is influenced not only by local coastal processes in Bengkulu but also by broader regional factors, including the north–south orientation of the coastline and the strong thermal contrast imposed by the Indian Ocean (Chang *et al.,* 2005; Yokoi *et al.,* 2017).

Taken together, these results demonstrate that the observed variability in divergence and in both zonal and meridional wind components arises from the interaction between the diurnal heating cycle, the land–sea breeze circulation, and the regional atmospheric environment. The robustness of the diurnal signal provides a fundamental framework for understanding coastal atmospheric dynamics in Bengkulu and establishes a physical basis for evaluating their implications for coastal environmental processes, such as nearshore ocean circulation and shoreline change (Small and Nicholls, 2003; Woodruff *et al.,* 2021).

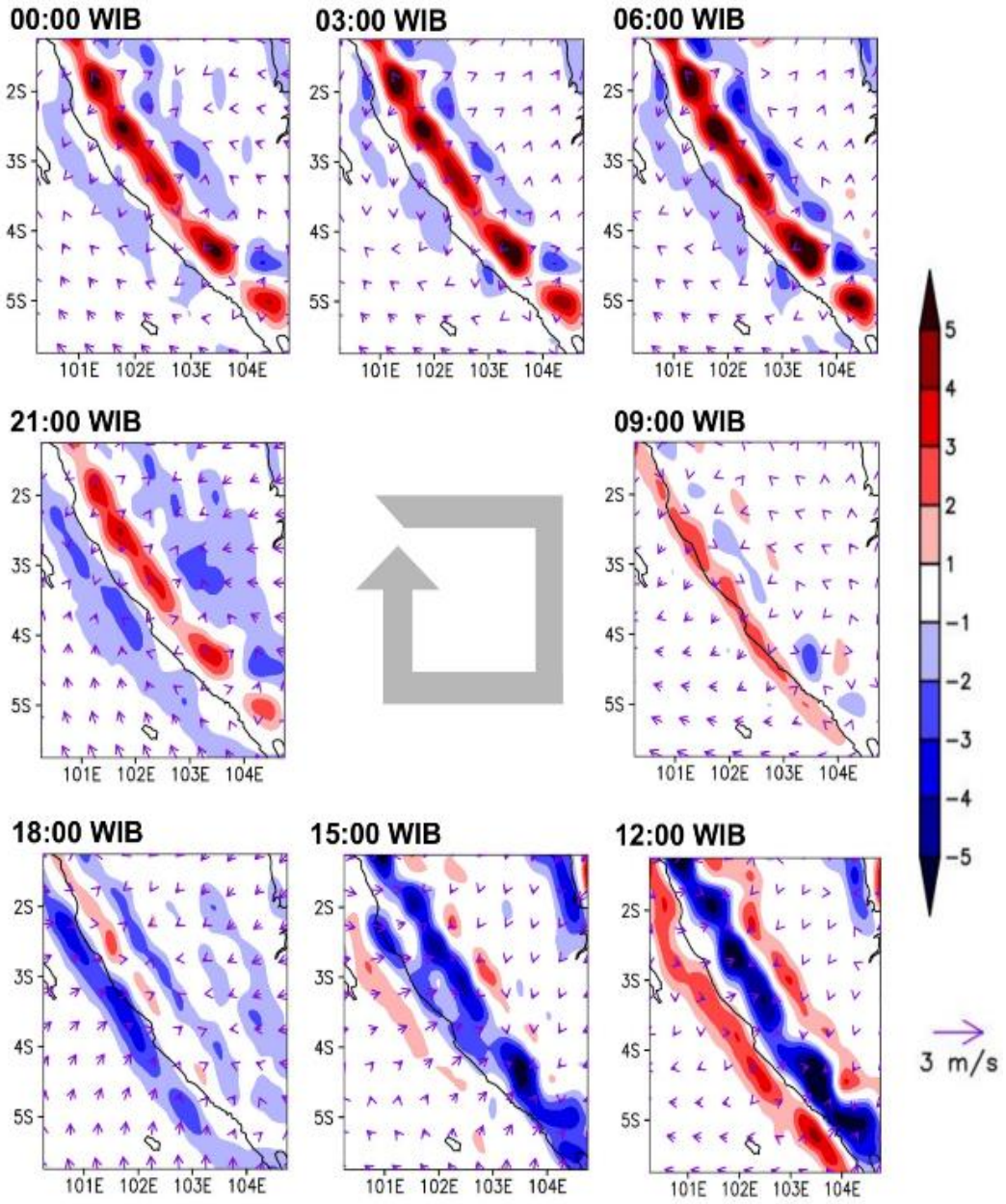

Figure 1. Anomalies in 5-year mean wind vectors (purple arrows; m s^{-1}) and divergence (shading; × 10^{-5} s^{-1}) at 3-hour intervals from 00:00 to 21:00 local time for September 2020–August 2025.

Figures 2–5 present the same variables as Figure 1 but averaged separately for each season (SON, DJF, MAM, and JJA). These seasonal composites reveal that, while the diurnal divergence patterns remain broadly consistent with the climatological mean, distinct seasonal variations are evident in the zonal and meridional wind fields. The persistence of the divergence structure across all seasons indicates that the land–sea thermal contrast remains the dominant and robust control on low-level convergence and divergence along the Bengkulu coast. Because the daily cycle of differential heating between land and ocean operates year-round, the timing and sign of divergence associated with the land–sea breeze circulation are largely preserved regardless of season (Qian *et al.,* 2010; Szkolka *et al.,* 2023).

In contrast, the seasonal differences observed in the wind fields reflect modulation by larger-scale background atmospheric circulation, most notably the Asian–Australian monsoon system. Across the seasonal cycle, the prevailing low-level winds over Maritime Continent, including western Sumatra, vary in both direction and strength in response to changing pressure gradients between the Asian continent, the Australian continent, and the surrounding ocean basins (Ramage, 1968; Chang *et al.,* 2005; Zhou *et al.,* 2009**).** These background flows interact with the locally generated land–sea breeze, either reinforcing, weakening, or reorienting it, thereby producing seasonal shifts in the zonal and meridional wind components while leaving the fundamental divergence–convergence pattern largely intact (Szkolka *et al.,* 2023; Vincent and Lane, 2017).

During the boreal winter (DJF), as shown in Figure 3, when northwesterly monsoon flow dominates the region, the large-scale onshore winds from the Indian Ocean tend to strengthen the daytime sea breeze but may suppress or distort the nighttime land breeze, resulting in more asymmetric wind structures (Chang *et al.,* 2005). In contrast, during the boreal summer (JJA), as shown in Figure 5, the prevailing southeasterly monsoon alters the orientation of the coastal wind field, leading to a different balance between zonal and meridional components while still supporting daytime convergence over land. The transitional seasons (SON and MAM) as shown in Figure 2 and Figure 4, are characterized by weaker background winds, allowing the locally driven land–sea breeze circulation to appear more symmetric and closely resemble the climatological mean pattern (Qian *et al.,* 2010; Ramage, 1968).

Despite the seasonal reorientation of the wind field, the divergence patterns remain broadly consistent throughout the year, with convergence and divergence values generally occurring within the same climatological range (approximately $\pm 5 \times 10^{-5}$ s^{-1}). In contrast, seasonal variability is more evident in the wind vectors, whose direction and magnitude respond to the evolving Asian–Australian monsoon system. Climatological wind speeds are typically on the order of 3–4 m s^{-1} but may increase to approximately 5–6 m s^{-1} during the peak monsoon seasons. These results indicate that seasonal atmospheric circulation primarily modulates the horizontal wind field, whereas the convergence–divergence structure remains largely controlled by the persistent diurnal land–sea thermal contrast.

The relative invariance of divergence patterns alongside pronounced seasonal shifts in wind direction suggests that divergence is primarily governed by vertical motion associated with surface heating contrasts, whereas horizontal wind vectors are more sensitive to the influence of regional-scale circulation (Miller *et al.,* 2003; Vincent and Lane, 2017). This distinction underscores the interaction between local diurnal forcing and seasonal monsoonal flow, in which the land–sea breeze persists throughout the year but is dynamically modified by the evolving large-scale atmospheric environment. Consequently, the seasonal wind variations evident in Figures 2–5 can be interpreted as the superposition of the diurnal coastal circulation onto the background monsoonal flow, rather than as a fundamental alteration of the underlying coastal atmospheric dynamics.

Recent studies focusing on the Indonesian Maritime Continent further reinforce the interpretation of the Bengkulu diurnal circulation as a robust yet dynamically modulated system. Analyses using high-resolution reanalysis products such as ERA5, together with surface and upper-air observations from BMKG, show that the diurnal cycle of low-level winds and divergence along the western coast of Sumatra is remarkably consistent throughout the year, while wind direction and intensity are strongly influenced by background monsoonal flow and intraseasonal variability (North *et al*., 2025; Szkolka *et al*., 2023; Zhu *et al.,* 2022).These studies demonstrate that the land–sea breeze remains the dominant driver of coastal convergence and divergence, but its expression in zonal and meridional wind components is

continuously adjusted by large-scale circulation, including the Madden–Julian Oscillation and monsoon surges.

More recent observational and modeling efforts have also highlighted the role of boundary-layer processes, gravity waves, and convectively generated density currents in shaping the diurnal wind structure over coastal Sumatra. Ship-borne radar observations and cloud-resolving simulations conducted along the southwestern coast of Sumatra reveal that these mesoscale features can modify the timing, vertical structure, and horizontal extent of the sea-breeze circulation without fundamentally altering the diurnal divergence pattern (Geng and Katsumata, 2023; Peatman *et al.,* 2023). This behavior is consistent with the present results, which show stable diurnal divergence signatures alongside seasonally shifting wind vectors. Collectively, recent Indonesia-focused studies confirm that coastal atmospheric dynamics in regions such as Bengkulu are governed by a persistent diurnal thermal forcing that is embedded within, and modulated by, evolving regional and intraseasonal atmospheric conditions.

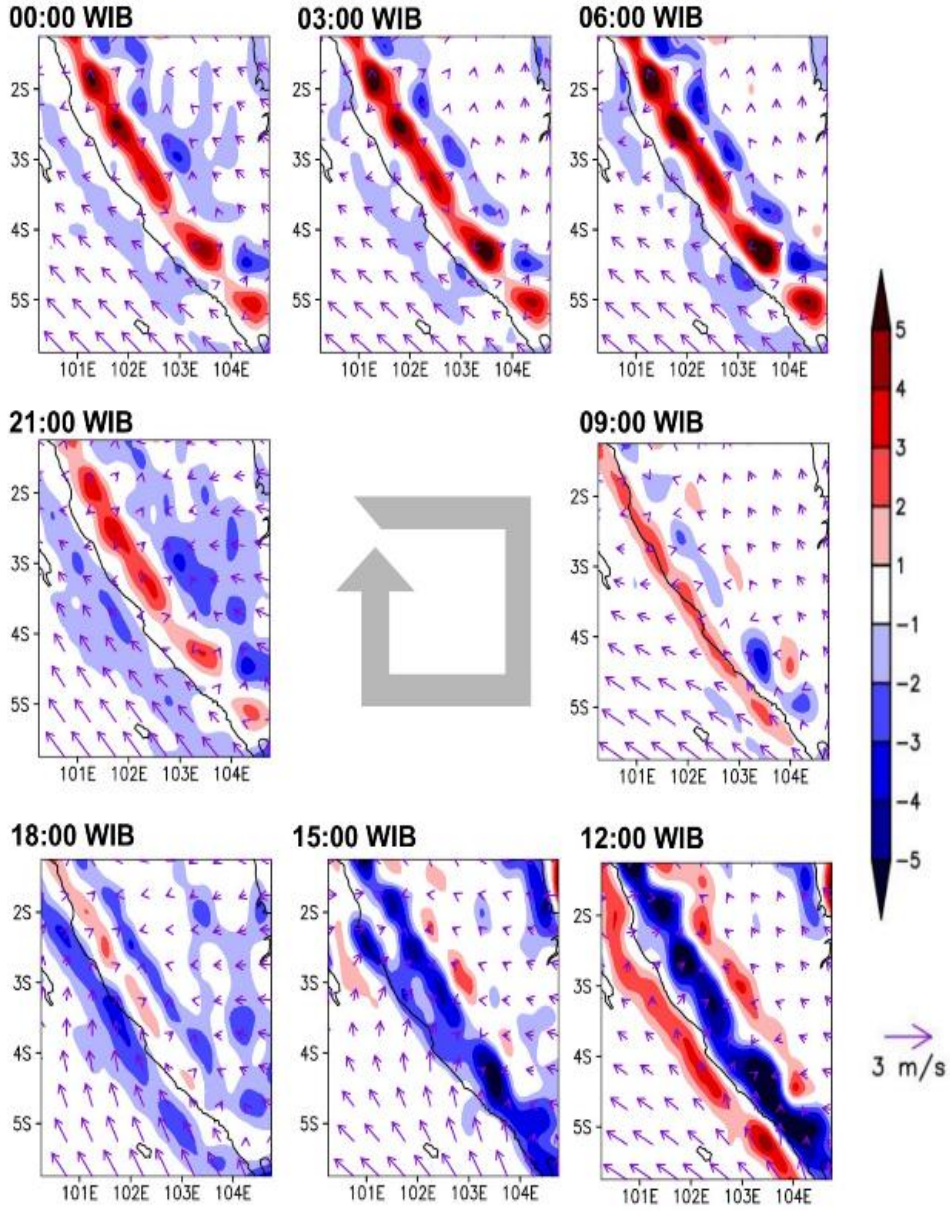

Figure 2. Anomalies in 5-year mean wind vectors (purple arrows; m s^{-1}) and divergence (shading; × 10^{-5} s^{-1}) at 3-hour intervals (00:00–21:00 local time) during DJF (December–February), averaged over the 2020/21–2024/25 seasons.

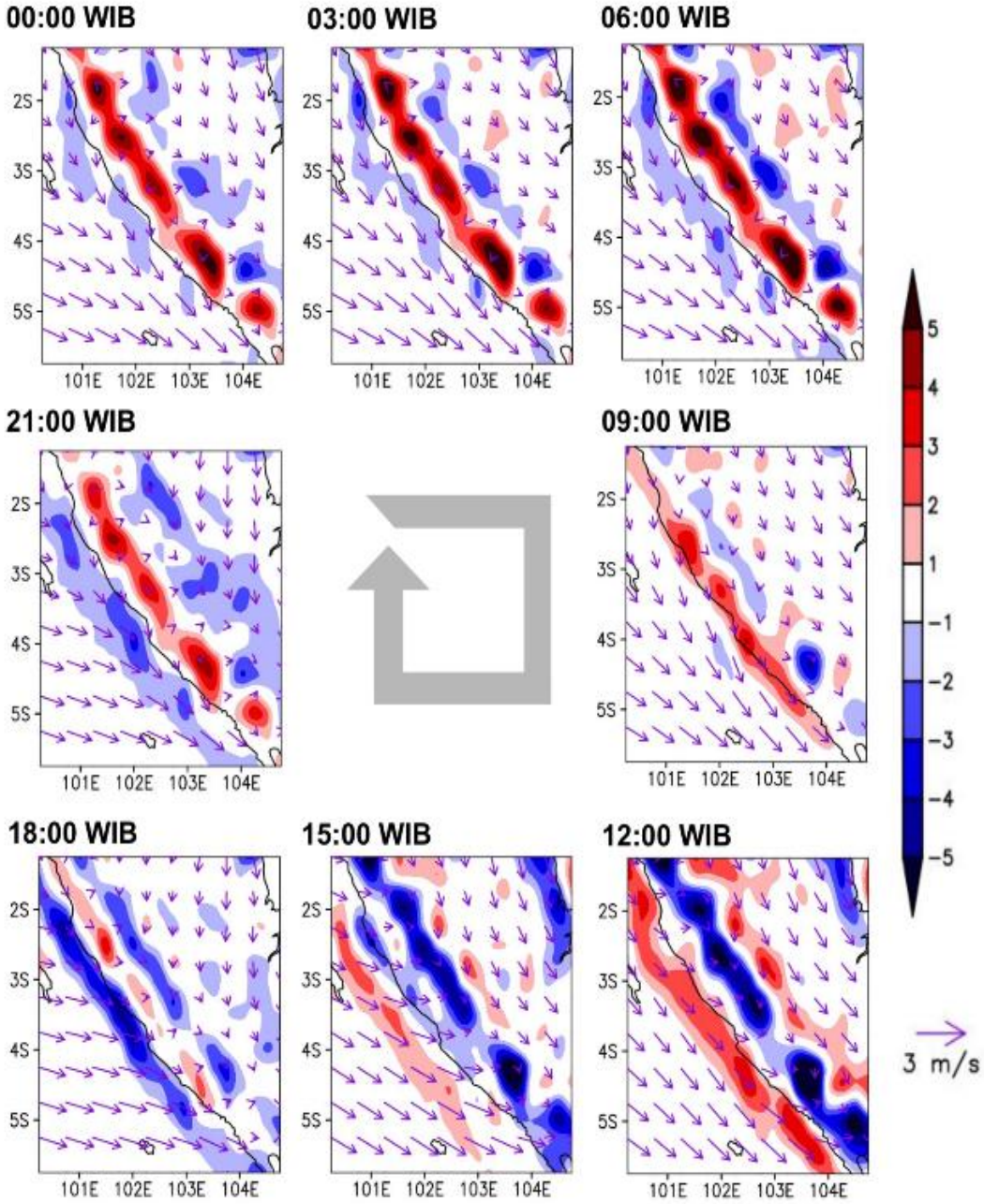

Figure 3. Anomalies in 5-year mean wind vectors (purple arrows; m s^{-1}) and divergence (shading; × 10^{-5} s^{-1}) at 3-hour intervals (00:00–21:00 local time) during DJF (December–February), averaged over the 2020/21–2024/25 seasons.

Figure 6 illustrates shoreline change along the Bengkulu coastal area as derived from the Digital Shoreline Analysis System (DSAS). Shoreline positions were extracted from Sentinel-2 Level-2A imagery with a spatial resolution of up to 10 m, resulting in a total of 163 shore-normal transects distributed along the Bengkulu coastline. The analysis covers the period from August 2020 to 2025. Based on DSAS outputs, shoreline behavior is classified into three categories: accretion (represented by green lines), stable shoreline conditions (yellow lines), and abrasion or erosion (red lines).

To specifically assess coastal abrasion, this study focuses on DSAS statistical parameters that are widely recognized as representative indicators of erosional processes. Previous DSAS-based studies indicate that shoreline abrasion is typically

associated with large-magnitude negative values, and literature that classifies extreme erosion commonly considers high negative rates as indicative of severe abrasion (Nassar *et al.,* 2019). However, it is important to note that there is no universally accepted threshold to define abrasion or accretion, as shoreline change processes are highly localized and influenced by site-specific environmental conditions.

Hastuti *et al.* (2022) stated that, based on various shoreline change studies using DSAS, shoreline changes are often categorized according to the magnitude of the Linear Regression Rate (LRR) or End Point Rate (EPR), where values less than −2 m/year indicate abrasion and values greater than +2 m/year indicate accretion, representing moderate to strong shoreline change. Furthermore, only shoreline changes that exceed statistical uncertainty measures, such as the Weighted Shoreline Error (WSE) or confidence interval (CI), are considered geomorphically significant. At the same time, the range of LRR and EPR values is strongly dependent on the temporal span of analysis, satellite image resolution, and local hydrodynamic conditions, including wave climate and coastal currents.

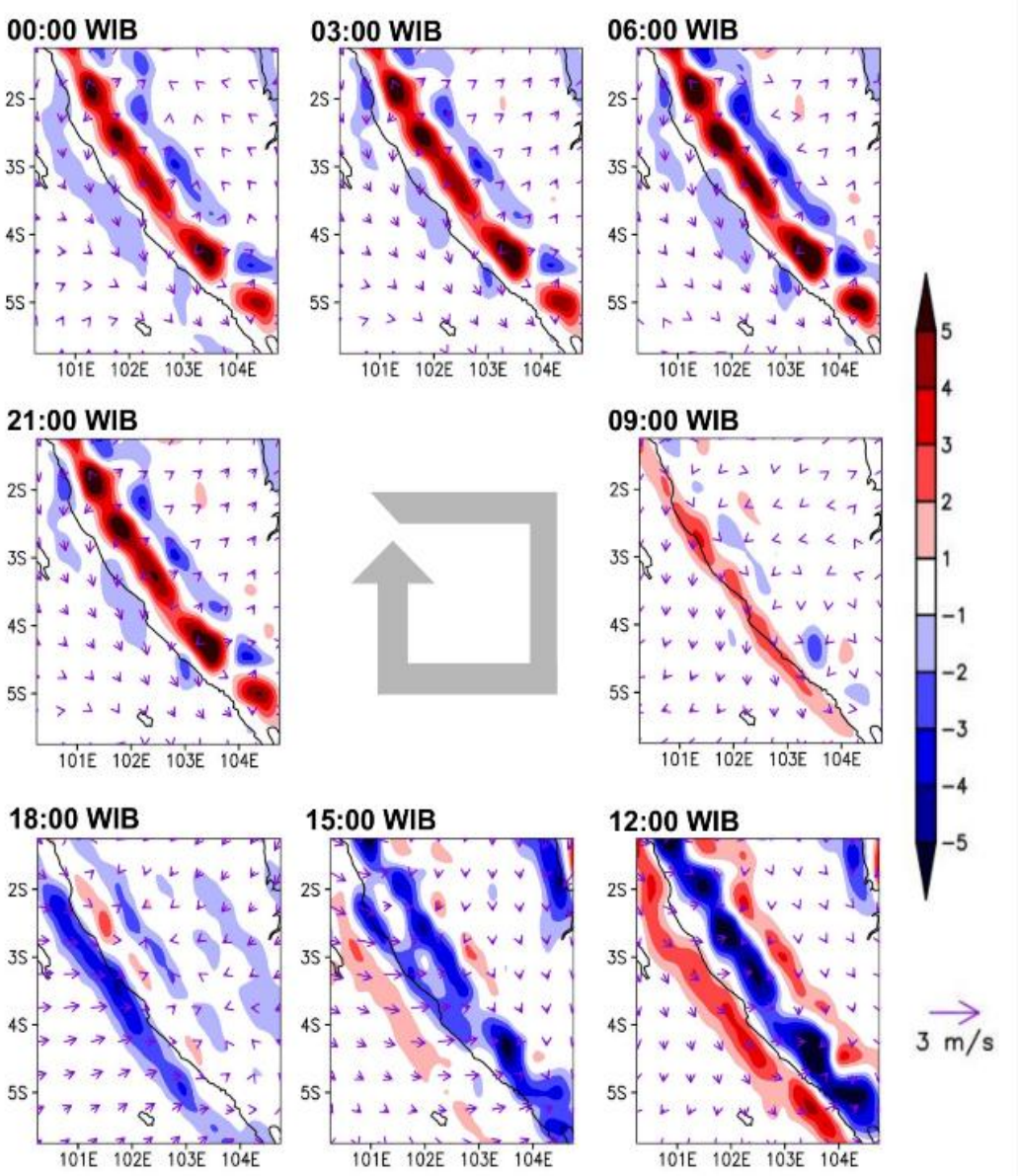

Figure 4.Anomalies in 5-year mean wind vectors (purple arrows; m s^{-1}) and divergence (shading; × 10^{-5} s^{-1}) at 3-hour intervals (00:00–21:00 local time) during MAM (March–May), averaged over the 2021–2025 seasons.

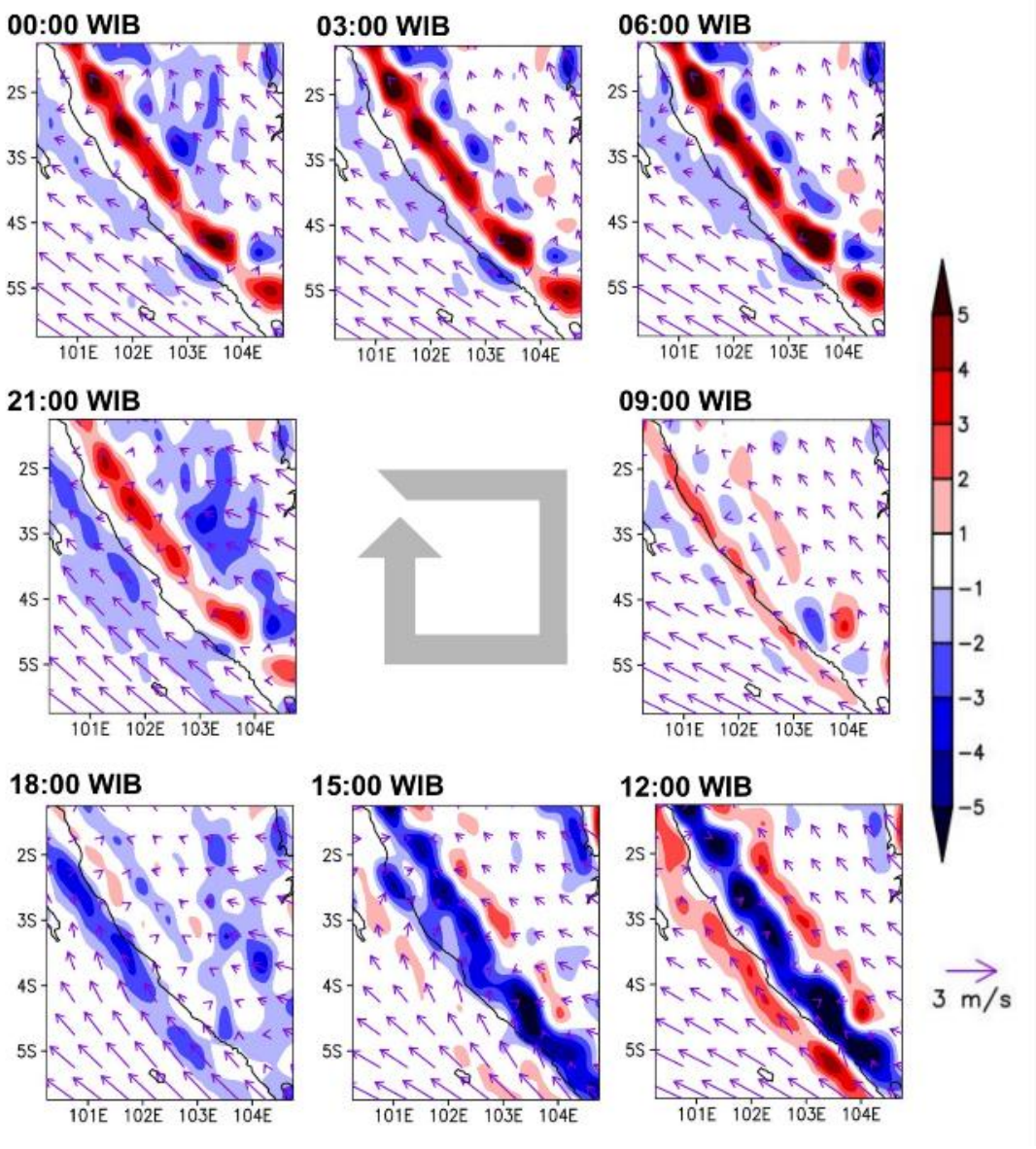

Figure 5. Anomalies in 5-year mean wind vectors (purple arrows; m s^{-1}) and divergence (shading; × 10^{-5} s^{-1}) at 3-hour intervals (00:00–21:00 local time) during JJA (June–August), averaged over the 2021–2025 seasons.

In the present study, shoreline positions were extracted from cloud-free Sentinel-2 Level-2A imagery acquired during August of each year to maximize shoreline visibility and minimize contamination by cloud cover. Because image selection was primarily constrained by data availability and cloud-free coastal conditions, no explicit tidal correction was applied during shoreline extraction. Consequently, part of the observed shoreline variability may reflect differences in tidal stage at the time of image acquisition. Nevertheless, the shoreline-change assessment was based on six shoreline positions spanning a five-year period (2020–2025) rather than on individual shoreline observations. Furthermore, the identification of abrasion-prone segments was not based on a single DSAS metric, but on the combined interpretation of LRR, EPR, NSM, and WSE. The consistency among these indicators, together with the use of NDWI-derived shorelines from multi-temporal Sentinel-2 imagery, increases confidence that the detected abrasion hotspots represent persistent long-term shoreline change rather than short-term variability

associated with tidal fluctuations or positional uncertainty. Several studies adopt threshold values of approximately ±1 m/year as an initial reference for shoreline change interpretation, while rates exceeding ±4 m/year are generally regarded as strong or significant changes (Wahidin *et al.,* 2025). Following Thieler *et al.* (2009), shoreline change rates were evaluated together with their associated uncertainty statistics. Confidence intervals and standard error estimates were used to assess the reliability of the calculated rates and to support the interpretation of shoreline change patterns. In addition, different DSAS-derived statistics, such as Linear Regression Rate (LRR) and End Point Rate (EPR), are often used together to describe shoreline change patterns and to assess the consistency of observed erosion and accretion trends over time (Khurram *et al*., 2025).

Based on these considerations, this study adopts a threshold of LRR < −3 m/year as a conservative criterion for identifying abrasion-prone coastal segments. This value lies between commonly reported thresholds for moderate shoreline change (approximately ±1 to ±2 m year^{-1}) and strong shoreline change (> ±4 m year^{-1}), thereby allowing the analysis to focus on coastal sectors exhibiting persistent and geomorphically meaningful erosion while reducing the likelihood of classifying marginal shoreline fluctuations as abrasion. However, this threshold was not applied in isolation. Abrasion-prone segments were identified only when strongly negative LRR values were accompanied by consistent negative EPR and NSM responses and when the observed shoreline retreat exceeded the associated uncertainty estimates represented by WSE. Consequently, the classification of abrasion-prone areas was based on the combined interpretation of multiple DSAS indicators rather than on a single threshold criterion. Table 1 presents detailed information on coastal segments classified as "prone to abrasion." The results indicate that specific sections of the Bengkulu coastline, particularly transects 41–44, exhibit relatively high abrasion rates compared to other areas, suggesting localized zones of intensified shoreline retreat during the study period.

Figure 6. Annual shoreline change in Bengkulu to denote accretion (green lines), abrasion (red lines), and stable (yellow lines) from August 2020 to 2025.

The robust and persistent diurnal circulation identified along the Bengkulu coast provides an important atmospheric framework for interpreting the spatial patterns of shoreline abrasion detected in the DSAS analysis. The repeated daily alternation between nighttime offshore flow (land breeze) and daytime onshore flow (sea breeze) likely plays an important role in modulating nearshore hydrodynamics through its influence on surface wind stress, wave generation, and coastal current variability. During the daytime, the onshore-directed sea breeze may enhance the transfer of momentum from the atmosphere to the ocean surface, thereby contributing to local wave generation and modifications of nearshore hydrodynamic conditions. Over multi-year timescales, the cumulative effect of this repeated diurnal forcing can contribute to persistent shoreline retreat, particularly in areas where sediment supply is limited or where coastal geomorphology favors erosion (Segura *et al.,* 2018; Woodruff *et al.,* 2021).

The nighttime land-breeze phase, while generally associated with weaker winds, can also influence sediment dynamics by modifying nearshore circulation patterns and promoting offshore sediment transport, especially under conditions of background monsoonal flow or elevated wave energy. The convergence–divergence structure identified in the diurnal cycle suggests systematic vertical motion and pressure adjustments that may further enhance coastal jet formation and localized current intensification along the shoreline. Such processes have been shown to contribute to cross-shore sediment fluxes and shoreline instability in tropical coastal environments (Geng and Katsumata, 2023; Peatman *et al.,* 2023). When combined with strong seasonal background winds, these diurnally forced circulations can act as an effective mechanism for redistributing sediment away from the shoreline, thereby reinforcing long-term abrasion trends observed in DSAS metrics such as LRR, EPR, and NSM.

Importantly, the spatial coincidence between areas of pronounced abrasion (e.g., transects 41–44) and regions persistently influenced by strong diurnal wind convergence during the daytime suggests a coupling between atmospheric forcing and geomorphic response. Nevertheless, the concentration of severe shoreline retreat within these specific transects indicates that local geomorphological controls also play an important role in modulating coastal response. As shown in Figure 6, transects 41–44 are located within a concave shoreline segment that differs from the relatively straighter coastal sections along the Bengkulu coast. Such embayed coastal configurations can modify wave refraction patterns, redistribute wave energy along the shoreline, and alter longshore sediment transport pathways, resulting in spatially variable erosion and accretion rates (Dean and Dalrymple, 2002; Klein *et al.,* 2010; Short and Masselink, 1999). Consequently, the severe abrasion observed in this sector likely reflects the combined influence of persistent atmospheric forcing and local shoreline geometry that favors sediment removal and shoreline retreat.

While DSAS-derived shoreline change reflects the integrated outcome of multiple drivers—including waves, tides, sediment supply, and human activities—the presence of a stable and energetic diurnal atmospheric system provides a physically consistent explanation for why certain coastal segments experience sustained erosion

Table 1. Transects with dominant indicators of abrasion

Transect ID	LRR (m/th)	EPR (m/th)	NSM (m)	WSE (m)	Latitude	Longitude
40	−3.13	1.09	5.53	12.81	−3.7829970	102.2588283
41	−8.03	−2.50	−12.61	15.3	−3.7835164	102.2582063
42	−12.30	−4.70	−23.76	20.25	−3.7838749	102.2574768
43	−11.60	−6.76	−34.14	12.45	−3.7842334	102.2567602
44	−10.91	−9.03	−45.63	8.54	−3.7844112	102.2559068
56	−1.27	−0.52	−2.62	2.09	−3.7885450	102.2469277
57	−1.04	−1.99	−10.05	3.36	−3.7897586	102.2468398
71	−0.81	−1.42	−7.16	2.45	−3.8028035	102.2562703
148	−1.09	0	0	3.44	−3.8545002	102.2961477

rather than episodic or random fluctuations. Recent studies emphasize that incorporating atmospheric diurnal variability into coastal erosion assessments improves the interpretation of satellite-derived shoreline trends, particularly in tropical regions where land–sea breeze systems are strong and persistent (Thieler *et al.,* 2009, Wahidin *et al.,* 2025). Therefore, the combined analysis of diurnal atmospheric circulation and DSAS-based shoreline change strengthens confidence that the identified abrasion-prone zones along the Bengkulu coast represent genuine and dynamically driven geomorphic responses rather than artifacts of short-term variability or observational uncertainty.

Although the spatial correspondence between abrasion-prone transects and regions characterized by persistent diurnal wind convergence suggests a physically plausible linkage between atmospheric forcing and shoreline change, the present study does not directly quantify wave conditions, longshore currents, or sediment transport processes. Therefore, the proposed mechanism should be interpreted as an inferred process supported by established coastal dynamics rather than definitive evidence of causality. Future studies integrating wave observations, hydrodynamic modeling, and sediment transport analyses would provide a more comprehensive assessment of the pathways through which diurnal atmospheric circulation influences shoreline evolution.

CONCLUSION

This study characterized the diurnal land–sea breeze circulation and documented micro-scale shoreline change along the Bengkulu coast during 2020–2025. The shoreline analysis identified substantial spatial variability, with localized abrasion and accretion zones and particularly persistent abrasion at transects 41–44. The consistent results across multiple DSAS metrics indicate that these segments represent important areas of ongoing shoreline retreat. The atmospheric analysis revealed a persistent diurnal circulation pattern throughout the year, characterized by nighttime land-breeze divergence over the coast and convergence offshore, followed by daytime sea-breeze convergence over land and divergence offshore. Although the diurnal circulation remained broadly consistent across seasons, its zonal and meridional components were modulated by the seasonal monsoon circulation. These results demonstrate that local land–sea thermal contrast is an important component of the coastal atmospheric circulation along Bengkulu. The spatial correspondence between areas of pronounced abrasion and regions influenced by recurrent diurnal circulation suggests a potential connection between local atmospheric forcing and shoreline evolution. However, the present analysis does not establish a direct causal relationship. Further observations of waves, currents, sediment characteristics, and sediment transport are needed to quantify the mechanisms linking diurnal wind forcing to shoreline change. The findings provide a baseline characterization of both coastal atmospheric variability and micro-scale shoreline evolution along the Bengkulu coast. More broadly, the study highlights the value of considering diurnal atmospheric variability alongside longer-term regional forcing when assessing coastal change. This integrated baseline can support future process-based investigations, coastal monitoring, and the development of more comprehensive approaches to coastal vulnerability assessment and management in Bengkulu and other tropical coastal environments.

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