

Shoreline Dynamics and Hydroclimatic Variability at the Ras Al-Katib Coastal Barrier, Al-Hodeidah, Yemen

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Abstract

Ras Al-Katib is a dynamic coastal barrier adjacent to the Port of Hodeidah on the Red Sea coast of Yemen, where shoreline instability may affect coastal infrastructure and navigation. This study quantifies shoreline change along a 5.6-km sector and evaluates its consistency with regional wind and offshore wave forcing. Multi-temporal satellite imagery from 2000, 2010, and 2020 was analysed using the Digital Shoreline Analysis System (DSAS), while hourly wind data (2000–2020) and ERA5 wave parameters (2001–2020) were assessed, with ERA5 evaluated against buoy observations from 2003–2004. DSAS revealed predominantly erosional behaviour in the central sector, with maximum shoreline retreat of approximately 109 m (5.5 m yr^{-1}), whereas the northern sector experienced accretion of approximately 93 m (4.66 m yr^{-1}). ERA5 showed good agreement with buoy-observed significant wave height ($r = 0.831$; $\text{RMSE} = 0.199 \text{ m}$; $\text{bias} = +0.005 \text{ m}$) and captured the broad directional regime, with 80.3% of estimates within $\pm 45^\circ$ of observations. Extreme-wave directions were strongly concentrated from the south ($175.4^\circ \pm 6.5^\circ$), consistent with the previously documented winter hydrodynamic setting. No significant trend was detected in offshore significant wave height during 2001–2020 ($p = 0.898$), nor in mean air temperature during 2000–2020 ($p = 0.450$). The spatially contrasting shoreline response is consistent with seasonal wind forcing and previously documented nearshore wave transformation that favours alongshore sediment redistribution. These findings provide a quantitative basis for coastal monitoring and adaptation planning and highlight the need to account for episodic wave forcing when assessing shoreline stability along the Red Sea coast of Yemen.

Keywords: Shoreline change, Coastal erosion, Coastal accretion, Ras Al-Katib, Hodeidah, DSAS, ERA5, Wave climate, Red Sea, Yemen

1 Introduction

Ras Al-Katib is a sandy and gravel bay barrier located along the Red Sea coast of Yemen, approximately 11 km north of Hodeidah Port. It serves as a natural protective feature for the commercial port and naval base by attenuating incoming wave energy

047 and moderating hydrodynamic forces. The barrier is separated from the port infras-
048 tructure by a navigational channel approximately 11 nautical miles in length, 200 m
049 in width, and 10–14.5 m in depth. Periodic hydrographic surveys conducted by the
050 Department of Maritime Affairs of Hodeidah Port have reported recurrent sediment
051 accumulation at various locations within the navigation channel, the naval base, and
052 adjacent coastal areas. These accumulations pose navigational hazards and require
053 repeated maintenance dredging.

054 Hodeidah Governorate is characterised by a tropical climate, with maximum tem-
055 peratures occasionally exceeding 54°C and mean annual rainfall of approximately 130
056 mm, falling predominantly during irregular torrential events (UN-Habitat, 2020). The
057 shoreline of Ras Al-Katib extends for approximately 11 km, with a mean width of 365
058 m, and is centred approximately at 14°50'N, 42°48'E. The irregular configuration of
059 the shoreline reflects ongoing erosion and accretion processes, which have resulted in
060 damage to coastal recreational facilities, restaurants, and public infrastructure.

061 Long-term climate projections for Yemen indicate a warming trend, with mean
062 annual temperatures expected to rise by 1.2–3.3°C by 2060 (IPCC, 2007). However,
063 analysis of the specific study period (2000–2020) reveals no statistically significant
064 trend in mean air temperature ($p = 0.450$), providing a stable baseline for isolating
065 the primary hydrodynamic drivers of shoreline change. Regional observations have
066 indicated warming rates of approximately 0.39°C per decade since the 1960s, with
067 the most pronounced increases during summer months (Ministry of Foreign Affairs
068 of the Netherlands, 2018; Mohamed, Elayah, & Schuplen, 2017). These longer-term
069 changes are anticipated to exacerbate coastal erosion, damage infrastructure, force
070 community relocations, and threaten marine ecosystems and low-lying coastal wet-
071 lands (Climate Investment Funds, 2012). Nevertheless, the absence of a measurable
072 thermal trend during the 2000–2020 period suggests that slow-onset climatic variables
073 linked to regional warming, such as temperature-driven sea-level rise, are unlikely to
074 be the primary drivers of the rapid, highly localised shoreline displacement observed
075 at Ras Al-Katib during this timeframe.

076 Shoreline change is governed by multiple interacting factors, including beach
077 morphology, sediment grain size, tidal regime, wave climate, coastal currents, wind
078 patterns, sea-level rise, and anthropogenic land-use modifications. Both natural pro-
079 cesses and human interventions influence shoreline stability and alter adjacent coastal
080 habitats (Chen, Chen, Liu, et al., 2005; Cooper, Jackson, Navas, et al., 2004; Forbes,
081 Parkes, Manson, & Ketch, 2004; Lin & Pussella, 2017; Mujabar & Chandrasekar, 2013;
082 Orford, Forbes, & Jennings, 2002; Sesli, Karsli, Colkesen, & Akyol, 2009). Along the
083 Yemeni Red Sea coast, AbdulBaki, Bawazeer, Al-Qadasy, and AbolGhaith (2018) doc-
084 umented high accretion rates in Al-Salif (42 ha yr⁻¹), Al-Luhaiyah (36.5 ha yr⁻¹), and
085 Al-Munierah (28.5 ha yr⁻¹), while Al-Duraihimi district experienced erosion rates of
086 approximately 14.7 ha yr⁻¹. These patterns were attributed to wave action, coastal
087 currents, tidal processes, and human encroachment. Sagheer, Humade, and Al-Jabali
088 (2011) specifically identified erosion and accretion hotspots at Ras Al-Katib, reporting
089 rates of 43,549 m² yr⁻¹ and 17,955 m² yr⁻¹, respectively, for 1972–1985, and 2,842
090

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$\text{m}^2 \text{yr}^{-1}$ and $20,712 \text{ m}^2 \text{yr}^{-1}$ for 2000–2006. The predominance of accretion over erosion in recent decades was linked to anthropogenic shoreline modifications associated with port expansion and fishing harbour construction.

Satellite-based shoreline change analysis has emerged as an effective tool for monitoring coastal dynamics, as demonstrated by [Warnasuriya, Gunaalan, and Gunasekara \(2018\)](#); [Warnasuriya, Kumara, Gunasekara, et al. \(2020\)](#) and [Daswin Ebenezer and Kumar \(2023\)](#). High-resolution imagery from Google Earth Pro, combined with the Digital Shoreline Analysis System (DSAS) extension within ArcGIS, enables quantitative assessment of shoreline displacement over decadal timescales.

Given the strategic importance of Hodeidah Port, the recurrent sedimentation issues in its navigation channel, and the growing concern over climate change impacts, there is an urgent need to systematically assess shoreline changes along Ras Al-Katib. The present study aims to: (1) quantify the rates and patterns of shoreline erosion and accretion along the analysed 5.6-km sector of Ras Al-Katib for the period 2000–2020 using DSAS; (2) examine the relationships between shoreline change and seasonal wind patterns, wave transformation, and hydrodynamic forcing; (3) evaluate the offshore wave climate using ERA5 reanalysis data validated against in-situ buoy observations acquired near the FSO SAFER terminal (Fig. 1a); and (4) discuss the potential implications of observed shoreline changes for the Hodeidah navigation channel and coastal infrastructure within the context of meteorological forcing and anthropogenic modification.

2 Materials and Methods

2.1 Study Area

The study area encompasses the Ras Al-Katib coastal barrier, located approximately 11 km north of Hodeidah city on the Red Sea coast of Yemen (Fig. 1a). The barrier is centred approximately at $14^\circ 50' \text{N}$, $42^\circ 48' \text{E}$, and extends approximately 11 km in length with a mean width of 365 m. The shoreline analysis focused on the central and northern sectors of Ras Al-Katib, covering approximately 5.6 km of the total 11 km barrier length. This segment was selected because it encompasses the areas of active erosion and accretion identified in previous studies ([Iraqi, 2008](#); [Sagheer et al., 2011](#)). The site is characterised by a semi-diurnal tidal regime, with mean spring and neap tidal ranges of approximately 0.80 m and 0.44 m, respectively ([Iraqi, 2008](#)). The coastal plain experiences a tropical arid climate, with winter monsoon (December–March) and summer monsoon (June–September) periods, separated by transitional seasons in April–May and October–November.

The Ras Al-Katib barrier serves as a natural buffer protecting the Hodeidah commercial port and naval base from direct wave attack. The port is accessed via a navigation channel approximately 11 nautical miles in length, 200 m in width, and 10–14.5 m in depth (Fig. 1b). The shoreline configuration reflects active sedimentary processes, with historical records indicating alternating erosion and accretion along different sectors of the barrier.

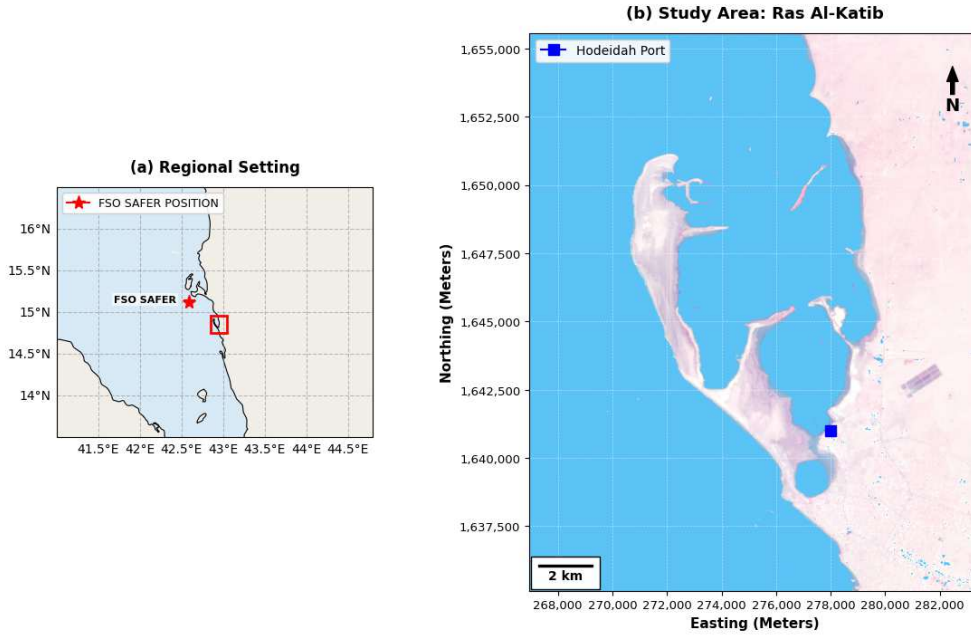


Fig. 1 Location map of the study area. (a) Regional setting along the Red Sea coast of Yemen, indicating the position of the FSO SAFER terminal (red star) providing the wave buoy data, and the spatial extent of the local study area (red box). (b) Detailed satellite view of the Ras Al-Katib coastal barrier derived from Landsat-8 imagery (acquired in 2018), highlighting the complex shoreline morphology and the location of Hodeidah Port (blue square). Coordinates in panel (b) are presented in UTM projection (metres).

2.2 Climatic and Wind Data

Wind and air-temperature data were obtained from the ERA5 reanalysis dataset (Hersbach, Bell, Berrisford, et al., 2020) via the Copernicus Climate Change Service (C3S) Climate Data Store. Hourly wind components (u and v) at 10 m height and 2 m air temperature were extracted for the period 2000–2020, corresponding to the availability of consistent buoy observations for wave validation. The spatial resolution of $0.25^\circ \times 0.25^\circ$ was used, with the nearest grid point to the Ras Al-Katib coastline selected to represent onshore conditions.

Wind data were processed to compute hourly wind speed and direction. Calm conditions were defined as wind speeds below 1.0 knots and were filtered out from the directional analysis to avoid statistical artefacts. Monthly and seasonal wind roses were constructed using the `openair` package (Carslaw & Ropkins, 2012) in R to visualise the directional frequency and speed distributions.

Temperature time-series analysis included the calculation of monthly and seasonal climatological means, as well as daily anomalies relative to the 2000–2020 baseline. Trend detection was performed using the non-parametric Mann-Kendall test, with Sen's slope estimator used to quantify the magnitude of any significant trends (Kendall, 1975; Mann, 1945; Sen, 1968). This approach was selected because it is

robust to outliers and does not assume a normal distribution of the data, making it suitable for hydroclimatic time-series analysis.

2.3 ERA5 Wave Data and Validation

To characterise the offshore wave climate and address the lack of long-term in situ wave measurements in the study area, this study utilised the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5; (Hersbach et al., 2020)). Hourly data for significant wave height (SWH) and mean wave direction (MWD) were extracted for the period 2001–2020 from the ERA5 single-level dataset at a spatial resolution of $0.25^\circ \times 0.25^\circ$. Data were obtained for the grid point closest to the study area offshore of Hodeidah.

To evaluate the suitability of ERA5 for this region, the reanalysis data were compared against available in situ observations from the Safer Exploration and Production Operation Company (SEPOC) for the overlapping period of 2003–2004. The observations were collected from a floating platform located approximately 60 km north-west of the study area, off the port of Ras Issa. Wave height measurements were obtained through visual estimation by an onboard observer and recorded manually on an hourly basis. Wave direction was determined based on the vessel’s heading at the time of observation. These measurement methods are subject to inherent uncertainties, including observer variability (particularly during night-time hours) and potential misalignment between vessel heading and true wave direction. Consequently, the buoy data should be regarded as approximate reference observations rather than high-accuracy instrumental measurements.

The comparison involved temporal matching of ERA5 data to the buoy records and calculation of the following statistical metrics for SWH: Pearson correlation coefficient (r), coefficient of determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Bias (ERA5 minus Buoy).

Because wave direction is a circular variable, directional agreement was evaluated using the circular difference between ERA5 and buoy directions rather than conventional linear correlation. The analysis included the mean directional bias, mean absolute angular error (MAE), root mean square angular error (RMSE), median absolute angular error, and the proportions of ERA5 estimates falling within $\pm 15^\circ$, $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$ of the buoy observations. Directional agreement was evaluated for the complete matched record, for buoy-defined extreme conditions (SWH > the 95th percentile), and at the peaks of declustered extreme events.

Extreme wave events were identified using the 95th percentile of buoy SWH (1.30 m). Exceedances were declustered using a runs approach with a run length of 12 consecutive non-exceedance observations. Because the merged record contained a small number of irregular temporal gaps, the run criterion was implemented in terms of consecutive observations rather than strictly elapsed hours.

2.4 Shoreline Extraction and Analysis

Shoreline positions for the years 2000, 2010, and 2020 were extracted from Multi-temporal satellite imagery available through Google Earth Pro version 7.3.4.8642. The

imagery dates, spatial resolutions, and sources are provided in Table S1 (Supplementary Material). The shoreline proxy used in this study was the instantaneous waterline at the time of image acquisition.

Tidal stage was considered as a potential source of uncertainty in shoreline extraction from the satellite imagery. The spring tidal range in the study area is approximately 0.80 m. Given the relatively low coastal slope, variations in water level may theoretically produce a horizontal displacement of the instantaneous waterline. However, this displacement cannot be equated directly with the full tidal range, because the magnitude and direction of horizontal waterline migration depend on the actual tidal stage at the time of image acquisition, local beach slope, and the specific shoreline proxy identified in the imagery.

The Google Earth Pro images acquired for 2000, 2010, and 2020 were therefore used primarily to characterise the decadal-scale spatial and temporal pattern of shoreline change using DSAS, rather than to determine the instantaneous position of the waterline. While tidal fluctuations represent an inherent unquantified uncertainty in the satellite-derived shoreline positions, the magnitude of the observed long-term morphological changes, including maximum retreats exceeding 100 m, is substantially greater than the positional variability expected from short-term water-level fluctuations alone. Accordingly, tidal uncertainty is not expected to alter the overall interpretation of the pronounced erosional and accretional patterns, although it may contribute to uncertainty in the absolute shoreline positions and estimated rates.

In addition to tidal variability, the total shoreline positional uncertainty was estimated by combining the following components:

1. **Image georeferencing uncertainty:** Approximately $\pm 1\text{--}2$ m based on Google Earth Pro specifications.
2. **Digitisation uncertainty:** Approximately ± 0.5 m based on repeated manual digitisation.
3. **Tidal/water-level uncertainty:** Recognised as a potential source of error, though not quantitatively corrected due to the unavailability of tidal stage data at the time of each image acquisition.

The extracted shorelines were imported into ArcGIS 10.6 software for spatial analysis using the Digital Shoreline Analysis System (DSAS) version 5.0 extension (Himmelstoss, Henderson, Kratzmann, & Farris, 2018). DSAS generates orthogonal transects at specified intervals along a baseline and calculates shoreline change statistics at each transect intersection. For this study, transects were generated at 100 m intervals along the Ras Al-Katib shoreline, resulting in 56 transects. The analysed shoreline segment covered approximately 5.6 km of the total 11 km barrier length.

Two statistical methods were employed to quantify shoreline change:

1. **Net Shoreline Movement (NSM):** The distance (in metres) between the oldest and youngest shorelines for each transect. Positive values indicate accretion (seaward movement), while negative values indicate erosion (landward movement).
2. **End Point Rate (EPR):** Calculated by dividing NSM by the elapsed time period between the two shorelines (in metres per year).

For short-term change assessment, EPR was calculated for the sub-periods 2000–2010 and 2010–2020, in addition to the full 2000–2020 period.

3 Results

3.1 Wind Regime and Seasonal Variability

Analysis of the ERA5 hourly wind data for the period 2000–2020 demonstrates a highly active and distinctly seasonal wind regime along the Ras Al-Katib coastline, which serves as a primary driver for nearshore hydrodynamics. Calm conditions (≤ 1.0 knots) are exceedingly rare, occurring only 0.91% of the time throughout the 21-year observation period.

The wind climate is characterised by a pronounced seasonal directional reversal (Figs. 2 and 3). During the winter season (December–March), winds are predominantly from the South (S), with a mean speed of 7.94 knots. This southerly forcing shifts dramatically during the summer monsoon (June–September), where the dominant wind direction reverses to the North-West (NW) and intensifies, reaching a seasonal mean of 8.46 knots, with July recording the highest monthly average at 9.43 knots.

The transitional seasons of spring (April–May) and autumn (October–November) exhibit moderate mean speeds (7.54 and 6.54 knots, respectively) and capture the directional shifts between the two primary monsoonal phases, though southerly winds generally maintain dominance. This robust seasonal bimodal wind distribution (S vs. NW) provides a clear meteorological mechanism for the alternating alongshore currents and nearshore wave transformations that drive the observed spatial patterns of erosion and accretion along the barrier.

3.2 Air Temperature and Climatology

Time-series analysis of the daily mean air temperature derived from ERA5 for the specific study period (2000–2020) indicates a mean annual temperature of 29.61°C , with absolute minimum and maximum values of 18.74°C and 39.04°C , respectively. The seasonal regime is well-defined, with mean temperatures peaking during the summer (32.82°C) and reaching their lowest during winter (26.09°C). Monthly climatology shows July as the warmest month (33.35°C) and January as the coolest (25.18°C).

Crucially, Mann-Kendall trend analysis applied to this 21-year window reveals no statistically significant annual warming trend ($p = 0.4503$), yielding a negligible Sen’s slope of $+0.007^{\circ}\text{C yr}^{-1}$. This thermal stability is consistent across the primary seasons, as neither winter ($p = 0.8800$) nor summer ($p = 0.2906$) exhibited significant linear trends over the study period (Fig. 4). The absence of a pronounced temperature trend during 2000–2020 contrasts with longer-term regional projections but provides a critical baseline for isolating the primary drivers of shoreline displacement during this specific timeframe.

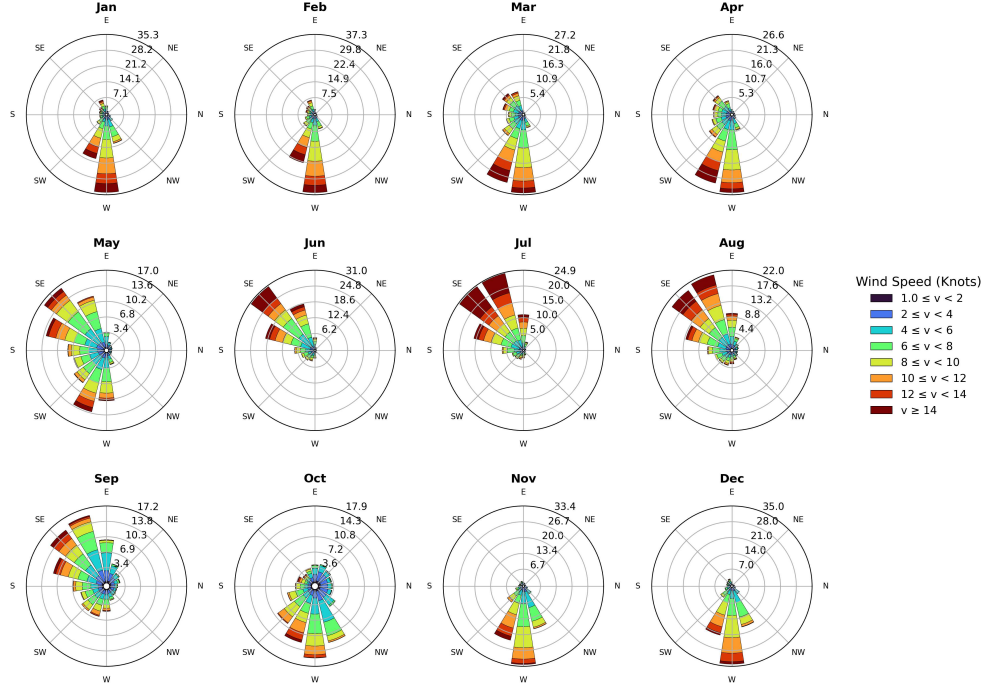


Fig. 2 Monthly wind rose diagrams for the Ras Al-Katib coastline (2000–2020). The panels illustrate the frequency of occurrence (%), wind speed (in knots), and dominant active directions across the twelve months, filtering out calm conditions (≥ 1.0 knots).

3.3 ERA5 Validation and Offshore Wave Climate

3.3.1 ERA5–Buoy Comparison

The ERA5 reanalysis was evaluated against available in-situ buoy observations for the overlapping period 2003–2004 (Table 1). A total of 17,428 temporally matched observations were available after merging and quality control. As noted in Section 2.3, the buoy observations were based on visual estimation by an onboard observer and manual recording, with wave direction inferred from vessel heading. These data should therefore be regarded as approximate reference observations rather than high-accuracy instrumental measurements, and the validation statistics presented below should be interpreted as indicating consistency between ERA5 and the available observational estimates rather than an absolute measure of ERA5 accuracy.

For significant wave height, ERA5 demonstrated good agreement with the buoy estimates. The mean SWH was 0.5095 m for ERA5 and 0.5044 m for the buoy, corresponding to a small positive bias of +0.0051 m. The Pearson correlation coefficient was high ($r = 0.831$, $p < 0.001$), while the coefficient of determination ($R^2 = 0.690$) indicated that approximately 69% of the linear variance in buoy-estimated SWH was explained by ERA5. The RMSE and MAE were 0.1992 m and 0.1511 m, respectively. However, ERA5 exhibited a lower standard deviation (0.2678 m) than the buoy

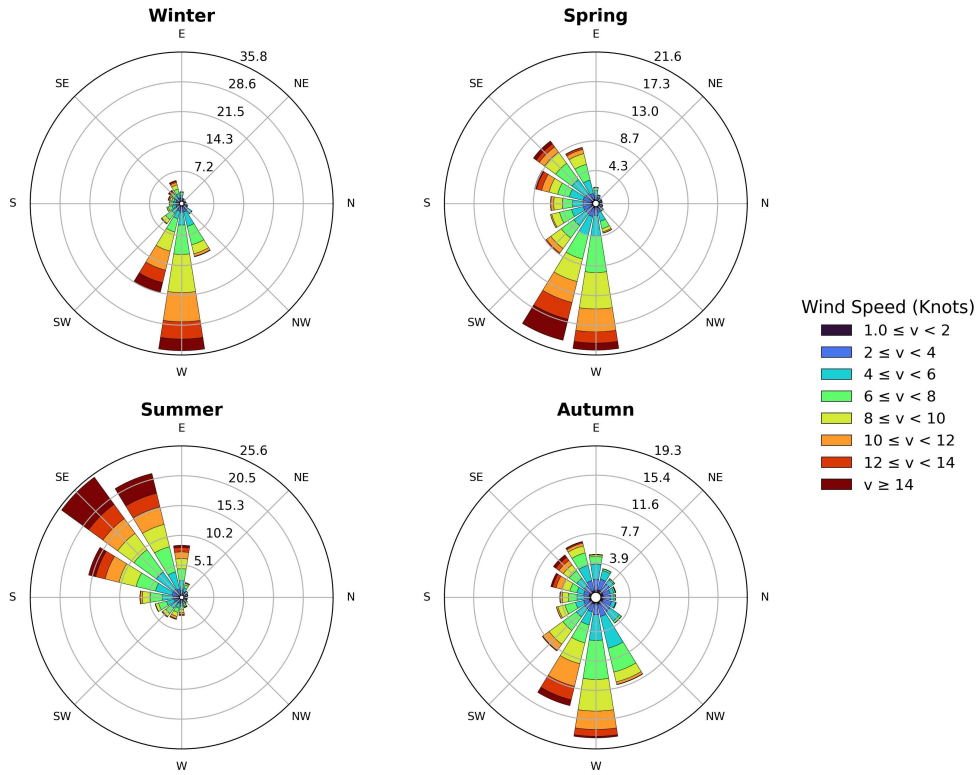


Fig. 3 Seasonal wind rose diagrams for the 2000–2020 observation period. The bimodal directional regime is clearly highlighted, transitioning from a dominant southerly (S) flow during Winter, Spring, and Autumn, to a strong north-westerly (NW) flow during the Summer monsoon.

estimates (0.3544 m), indicating that the reanalysis tended to smooth part of the short-term variability observed in situ.

For mean wave direction, the circular mean was 233.7° for ERA5 and 215.1° for the buoy record; the mean of the signed circular directional differences was $+6.7^\circ$. The proportions of ERA5 directional estimates falling within $\pm 15^\circ$, $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$ of the buoy observations were 44.8%, 70.2%, 80.3%, and 86.2%, respectively. These results indicate reasonable reproduction of the observed directional wave regime, although the lower agreement at the narrower angular thresholds indicates non-negligible directional discrepancies. Given that wave direction was inferred from vessel heading rather than measured independently, this level of agreement is considered satisfactory.

3.3.2 Directional Behaviour During Extreme Wave Conditions

Extreme wave conditions were defined using the 95th percentile of buoy-observed SWH, corresponding to a threshold of 1.30 m. A total of 579 observations exceeded this threshold. The circular mean wave direction was 175.4° for the buoy and 187.8° for ERA5. The mean directional bias was $+12.4^\circ$, with a MAE of 12.4° and RMSE of

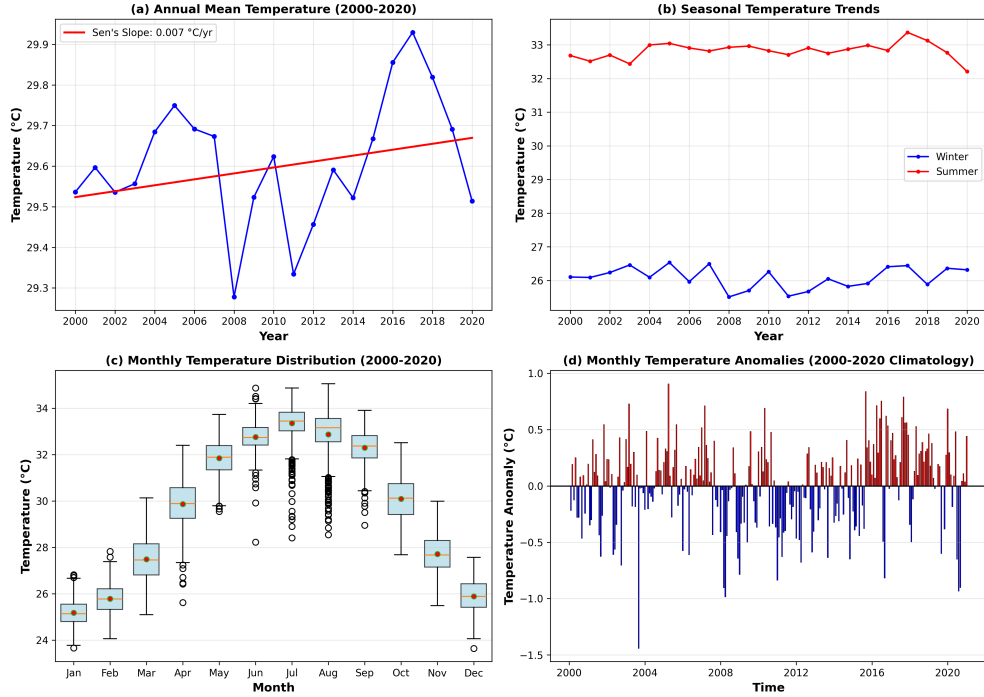


Fig. 4 Air temperature climatology and trends (2000–2020) at Ras Al-Katib. (a) Annual mean temperatures with Sen's slope indicating no significant linear trend. (b) Seasonal temperature stability for Winter and Summer. (c) Monthly boxplot distribution highlighting seasonal extremes. (d) Daily temperature anomalies relative to the 21-year baseline.

Table 1 Statistical comparison of ERA5 and in-situ buoy wave parameters for 2003–2004.

Metric	ERA5	Buoy	Comparison
SWH			
Mean (m)	0.5095	0.5044	Bias = +0.0051 m
Standard deviation (m)	0.2678	0.3544	—
Correlation (r)	—	—	0.8306 ($p < 0.001$)
Coefficient of determination (R^2)	—	—	0.6898
RMSE (m)	—	—	0.1992
MAE (m)	—	—	0.1511
MWD			
Circular mean (°)	233.7	215.1	—
Mean directional bias (°)	—	—	+6.7
Within $\pm 15^\circ$ (%)	—	—	44.8
Within $\pm 30^\circ$ (%)	—	—	70.2
Within $\pm 45^\circ$ (%)	—	—	80.3
Within $\pm 60^\circ$ (%)	—	—	86.2

13.4°. Despite this directional offset, 72.7% of ERA5 estimates were within $\pm 15^\circ$ and 99.7% were within $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$ of the buoy observations.

Declustered analysis identified 35 independent extreme-event clusters. The circular mean direction of buoy peak waves was 172.6° , compared with 186.8° for ERA5 at the corresponding peak times. The mean directional bias at the peaks was $+14.3^\circ$, with a MAE of 14.3° and RMSE of 17.1° . Approximately 97.1% of ERA5 estimates were within $\pm 45^\circ$ of the observed peak directions. In contrast, ERA5 underestimated peak SWH in 94.3% of the cases, with a mean ERA5-to-buoy SWH ratio of 0.706. This indicates that ERA5 reproduced the dominant directional regime considerably better than the magnitude of individual extreme wave peaks.

3.3.3 Temporal Variability of Offshore Wave Height

Analysis of the ERA5 time series for the period 2001–2020 revealed no statistically significant long-term trend in annual mean significant wave height. Linear regression applied to the annual mean SWH yielded a slope not significantly different from zero ($p = 0.898$). The corresponding 95% confidence interval for the slope included zero, confirming the absence of a detectable trend. This result indicates that, during the study period, there was no detectable systematic increase or decrease in mean offshore wave energy reaching the study area. However, the directional characteristics of the most energetic wave conditions, which may be more relevant to sediment transport and shoreline change, are examined separately in the following section.

3.3.4 Directional Characteristics of High-Wave Conditions

Directional analysis of the matched buoy–ERA5 observations provided additional observational evidence relevant to the hydrodynamic setting of the Ras Al-Katib coastal barrier. Two wave-height thresholds were examined: the upper-third threshold (P66.7, corresponding to the 66.7th percentile) and the extreme-wave threshold (P95, corresponding to the 95th percentile). The P66.7 threshold was used to characterise relatively high-wave conditions, whereas P95 was used to isolate the most energetic 5% of observations.

For the upper-third wave-height conditions (SWH > 0.50 m), 5,666 observations, representing 32.51% of the 17,428 matched records, were retained. The circular mean wave direction was 180.6° , with a circular standard deviation of 42.3° . The southerly sector (S) was strongly dominant, accounting for 82.81% of the observations, while the north-western sector (NW) represented a secondary contribution of 10.57% (Table 2). The relatively large circular standard deviation indicates substantially greater directional dispersion within this broader high-wave population.

For the P95 threshold (SWH > 1.30 m), 579 observations (3.32% of the matched record) were analysed. The circular mean direction was 175.4° , with a markedly smaller circular standard deviation of 6.5° . The southerly sector accounted for 98.79% of the P95 observations, with the remaining 1.21% occurring in the south-eastern sector. Thus, the most energetic wave conditions exhibited a highly concentrated southerly directional regime, in contrast to the broader directional distribution observed for the upper-third wave-height population (Fig. 5a). This pronounced stratification is clearly

visible across the entire dataset, where the highest magnitude events are exclusively confined to a narrow southerly angular band (Fig. 5b).

The strong concentration of P95 wave directions around the southerly sector provides an observational constraint on the directional component of the regional wave climate during energetic conditions. The P95 mean direction of 175.4° lies close to the previously documented winter SSW reference direction ($\sim 200^\circ$) used to characterise the regional hydrodynamic setting reported by Iraqi (2008). This directional agreement should be interpreted as hydrodynamic consistency rather than as direct evidence of causality, because the present analysis does not explicitly resolve nearshore wave transformation, wave-induced currents, or sediment transport pathways. Nevertheless, the pronounced directional concentration of the highest waves is consistent with the previously proposed hydrodynamic interpretation of the observed shoreline-change pattern and provides independent observational support for that interpretation.

Table 2 Directional statistics for high-wave conditions based on the P66.7 and P95 significant wave-height thresholds.

Parameter	P66.7 (Upper Third)	P95
Threshold (m)	0.50	1.30
Number of records	5,666	579
Percentage of total (%)	32.51	3.32
Circular mean direction ($^\circ$)	180.6	175.4
Circular standard deviation ($^\circ$)	42.3	6.5
Dominant sector	S (82.81%)	S (98.79%)
Secondary sector	NW (10.57%)	SE (1.21%)

3.4 Shoreline Change Analysis

3.4.1 Net Shoreline Movement (NSM) — Total Distance of Change

The Digital Shoreline Analysis System (DSAS) applied to the 2000–2020 period revealed pronounced spatial variability in shoreline behaviour along the analysed 5.6-km sector of the Ras Al-Katib barrier (Fig. 6, Table 3). Out of the 56 evaluated transects, 40 (71.43%) displayed negative NSM values, signifying erosion, whereas 16 transects (28.57%) exhibited positive values, indicating accretion.

The maximum shoreline retreat (erosion) reached an NSM of -109.95 m at transect ID 23, situated in the central sector of the barrier. The mean retreat distance across all erosional transects was -24.9 m. Conversely, the maximum seaward advance (accretion) was recorded at 93.14 m at transect ID 3, located at the northern terminus of the barrier, yielding a mean accretion distance of 25.3 m across the advancing transects.

3.4.2 End Point Rate (EPR) — Annual Rates of Change

The EPR analysis for the comprehensive 2000–2020 observation period yielded a mean rate of -0.56 ± 0.72 m yr $^{-1}$ across the entire study area. Consistent with the NSM

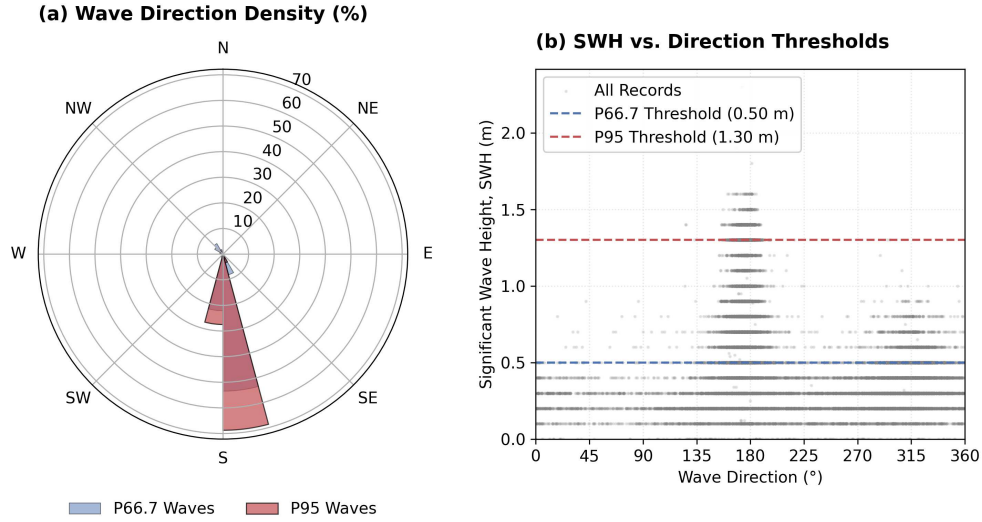


Fig. 5 Directional characteristics of high-wave conditions at Ras Al-Katib. (a) Wave direction density (%) presented as a polar wave rose, comparing the relative frequency distributions of the P66.7 (blue) and P95 (red) wave-height thresholds; (b) scatter plot of significant wave height (SWH) against wave direction for all matched records, with dashed horizontal lines denoting the established P66.7 and P95 thresholds.

findings, 71.43% of the transects experienced erosion, whilst 28.57% underwent accretion. The most severe erosional rate, -5.50 m yr^{-1} , was identified in the central sector (transect ID 23), with the mean erosional rate standing at -1.24 m yr^{-1} . In contrast, the peak accretional rate of 4.66 m yr^{-1} occurred at the northern extremity (transect ID 3), with an average accretional rate of 1.33 m yr^{-1} .

Furthermore, a sub-period analysis (2000–2010 and 2010–2020) demonstrated temporal consistency in the erosional trends within the central sector across both decades. However, the accretional dynamics at the northern end intensified, becoming notably more pronounced during the latter decade.

4 Discussion

4.1 Meteorological Forcing and Hydrodynamic Consistency

The directional analysis provides additional observational evidence for interpreting the spatially heterogeneous shoreline response at Ras Al-Katib, particularly when contextualised with the regional meteorological forcing. The wind analysis spanning 2000–2020 demonstrates a pronounced seasonal bimodal regime, characterised by prevailing southerly winds during the winter and a shift to north-westerly dominance in the summer. This meteorological pattern directly influences the regional wave climate.

The most energetic wave conditions (P95; $\text{SWH} > 1.30 \text{ m}$) were strongly directionally concentrated, with a circular mean of 175.4° and a circular standard deviation

Table 3 Summary of shoreline change statistics using NSM and EPR methods for Ras Al-Katib (2000–2020)

Parameter	NSM (m)	EPR (m yr ⁻¹)
Total transects	56	56
Mean distance/rate	−10.56	−0.56
Erosional transects (n)	40	40
Erosional transects (%)	71.43	71.43
Accretional transects (n)	16	16
Accretional transects (%)	28.57	28.57
Max erosion	−109.95	−5.50
Max erosion transect ID	23	23
Mean erosion	−24.9	−1.24
Max accretion	93.14	4.66
Max accretion transect ID	3	3
Mean accretion	25.3	1.33

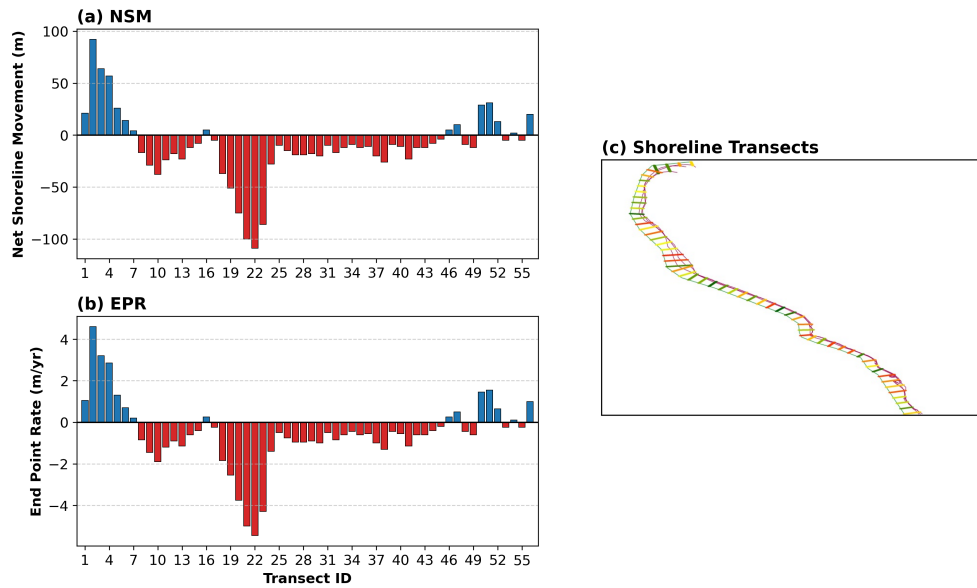


Fig. 6 Shoreline change analysis along the Ras Al-Katib barrier. (a) Net Shoreline Movement (NSM) and (b) End Point Rate (EPR) representing the overall period from 2000 to 2020. (c) Spatial distribution of the generated transects along the sand spit.

of 6.5°; 98.79% of P95 observations occurred within the southerly sector. This indicates that extreme wave energy is primarily coupled with the winter southerly wind regime. The P95 direction is broadly consistent with the previously documented winter south-to-south-westerly hydrodynamic regime reported by Iraqi (2008), although the observed mean direction (175.4°) should not be treated as an exact match to the reference direction ($\sim 200^\circ$).

Iraqi (2008) further reported, from SWAN modelling, wave convergence in the central sector and wave diffraction near the northern end, processes proposed to explain the observed central erosion and northern accretion. The present wind and wave observations provide robust empirical support for that modelled configuration, strengthening its physical plausibility. Furthermore, the seasonal shift to north-westerly winds during the summer likely generates corresponding alongshore currents, contributing to sediment redistribution. Overall, the strong directional concentration of energetic waves and the seasonal wind reversal provide a coherent observational constraint on the hydrodynamic interpretation of shoreline change at Ras Al-Katib. This evidence is complementary to, rather than a replacement for, direct modelling or measurement of nearshore sediment transport.

4.2 Offshore Wave Climate and Its Hydrodynamic Relevance

While the nearshore transformation mechanisms explain the spatial patterns of erosion and accretion, understanding the temporal variability of the energy driving these processes requires an assessment of the offshore wave climate. Validation of ERA5 against in situ buoy observations demonstrated good agreement in significant wave height ($r = 0.831$, $\text{RMSE} = 0.199$ m, $\text{bias} = +0.005$ m) and a reasonably accurate representation of the offshore wave-direction regime, with 80.3% of estimates falling within $\pm 45^\circ$ of buoy observations. Directional agreement remained robust during extreme conditions ($\text{SWH} > 1.30$ m), with 97.1% of declustered peak events falling within $\pm 45^\circ$. However, ERA5 exhibited lower variability (standard deviation = 0.268 m) than the buoy observations (0.354 m), indicating some smoothing of short-term wave-height variability. More importantly, ERA5 underestimated peak SWH in 94.3% of independent extreme events, with a mean ERA5-to-buoy ratio of 0.706. Thus, ERA5 reliably represents the broad offshore wave regime but does not fully reproduce the magnitude of individual extreme wave peaks.

This limitation is important when interpreting long-term wave-climate behaviour. Although ERA5 data for 2001–2020 showed no significant trend in annual mean offshore SWH ($p = 0.898$), the absence of a trend in mean conditions does not exclude geomorphically important episodic forcing. In sandy coastal systems, substantial shoreline displacement can result from short-lived energetic events rather than changes in mean wave conditions. Given the approximately 30% underestimation of observed extreme-wave heights by ERA5, the actual magnitude of extreme-event forcing may be considerably greater than indicated by the reanalysis. Therefore, the absence of a significant trend in mean SWH cannot be interpreted as evidence against extreme-wave forcing as a contributor to localised erosion at Ras Al-Katib. Quantifying this contribution would require high-resolution nearshore wave modelling capable of resolving extreme-event transformation and associated sediment-transport processes.



Fig. 7 The coastal facilities due to human activities along coastline of Ras Al-Katib

4.3 Implications for Hodeidah Navigation Channel and Coastal Management

The substantial sediment accretion observed at the northern end of Ras Al-Katib has potential implications for the Hodeidah navigation channel and naval base. The accumulated sediment may be transported into the channel by tidal and wave-induced currents, contributing to the sedimentation problems documented in periodic hydrographic surveys. While a direct sediment budget is required to confirm this pathway, the spatial proximity and hydrodynamic connectivity between Ras Al-Katib and the navigation channel suggest a plausible sediment source–sink relationship. The present study therefore identifies a plausible sediment-source relationship rather than demonstrating a quantified sediment flux.

The meteorological analysis of the 2000–2020 period indicates no statistically significant long-term trend in mean air temperature ($p = 0.450$). The absence of a measurable thermal trend over this two-decade period suggests that slow-onset variables linked to regional warming, such as temperature-driven sea-level rise, are unlikely to be the primary drivers of the rapid, highly localised shoreline displacement observed at Ras Al-Katib. Rather, the evidence points towards mechanical and hydrodynamic forcing—specifically, seasonal wind reversals and extreme wave events—alongside anthropogenic modifications. Effective coastal management in the Red Sea coastal zone of Yemen should therefore adopt an integrated approach that prioritises mitigating the impacts of intense hydrodynamic events and evaluating the long-term effects of coastal infrastructure.

4.4 Role of Human Activities

Anthropogenic modifications have substantially altered the shoreline configuration of Ras Al-Katib over recent decades. Port expansion (1972–1989), fishing harbour construction, jetty construction, and coastal infrastructure development have all contributed to shoreline changes (Sagheer et al., 2011). The construction of coastal recreational facilities without adequate environmental impact assessments may have locally modified shoreline behaviour and potentially contributed to erosion in vulnerable sectors (Fig. 7).

The relative contribution of human activities versus natural processes to the observed shoreline changes cannot be precisely quantified with the available data. However, the spatial coincidence of erosion hotspots with areas of intensive coastal development suggests that anthropogenic factors may have contributed to, or locally amplified, natural erosion processes.

4.5 Comparison with Regional Studies

The observed erosion at Ras Al-Katib (-5.5 m yr^{-1} maximum, -1.24 m yr^{-1} mean) occurs within a broader regional context of substantial shoreline instability along the Yemeni Red Sea coast. AbdulBaki et al. (2018) documented significant coastal changes in other parts of Hodeidah Governorate, including accretion in Al-Salif (42 ha yr^{-1}) and Al-Luhaiyah (36.5 ha yr^{-1}), and erosion in Al-Duraihimi district (14.7 ha yr^{-1}). Although these rates are expressed in different units (area-based vs. shoreline-distance-based), the overall pattern confirms that the Yemeni Red Sea coast is experiencing widespread shoreline adjustments. The alternating pattern of erosion and accretion along Ras Al-Katib is consistent with this broader regional pattern of shoreline instability.

The use of DSAS and Google Earth imagery in this study aligns with established methodologies for shoreline change analysis (Daswin Ebenezer & Kumar, 2023; Warnasuriya et al., 2018). The integration of ERA5 wave data adds a new dimension to shoreline change studies in the Red Sea region, where long-term in situ wave measurements are scarce.

4.6 Limitations and Uncertainties

Several limitations should be acknowledged when interpreting the results of this study. These limitations relate to the shoreline extraction methodology, the wave reanalysis validation, the hydrodynamic interpretation, and the spatial coverage of the analysis.

Shoreline extraction uncertainties.

The shoreline positions extracted from Google Earth Pro represent the instantaneous waterline at the time of image acquisition, rather than a fixed geomorphic datum such as the high-water line or vegetation line. Consequently, the reported shoreline-change rates reflect long-term morphological trends that are subject to positional uncertainty associated with tidal variability, wave run-up, and image acquisition timing. The spring tidal range in the study area is approximately 0.80 m, which, given the relatively low coastal slope, may theoretically produce horizontal displacement of the instantaneous waterline. However, this displacement cannot be equated directly with the full tidal range, as the magnitude and direction of horizontal waterline migration depend on the actual tidal stage at the time of image acquisition, local beach slope, and the specific shoreline proxy identified. A quantitative correction for tidal stage was not applied because the actual tidal level at the time of each historical image acquisition was not available. The reported shoreline-change rates should therefore be interpreted as long-term morphological trends subject to this positional uncertainty, rather than as tide-corrected instantaneous shoreline positions.

783 ***ERA5 validation constraints.***

784 The ERA5 reanalysis data, while validated against available buoy observations for
785 2003–2004, represent a modelled product rather than direct observations. Moreover,
786 as noted in Section 2.3, the buoy observations were based on visual estimation by
787 an onboard observer and manual recording, with wave direction inferred from vessel
788 heading. These methods introduce additional uncertainty, including observer variabil-
789 ity (particularly during night-time hours) and potential misalignment between vessel
790 heading and true wave direction. Consequently, the validation statistics presented in
791 Section 3.3 should be interpreted as indicating consistency between ERA5 and the
792 available observational estimates, rather than as an absolute measure of ERA5 accu-
793 racy. The validation period was limited to 2003–2004, and the performance of ERA5
794 may vary across different seasons or under extreme wave conditions. Nevertheless,
795 the good agreement in mean SWH and temporal variability, despite the approximate
796 nature of the buoy observations, supports the suitability of ERA5 for characterising
797 the offshore wave climate in this data-sparse region.

798
799 ***Hydrodynamic interpretation.***

800 The nearshore wave transformation patterns discussed in this study are based on
801 previous modelling by Iraqi (2008) rather than new simulations conducted as part of
802 this study. While this provides a plausible hydrodynamic context for interpreting the
803 observed shoreline changes, the modelling was based on historical bathymetric and
804 forcing conditions that may not fully reflect present-day conditions. Future work would
805 benefit from updated SWAN or other wave-model simulations using recent bathymetric
806 data and updated forcing conditions, including more recent wind and wave climate
807 data.

808
809 ***Sediment transport inference.***

810 The sediment transport pathways inferred from shoreline changes and hydrodynamic
811 patterns are hypothetical and based on the spatial consistency between observed
812 erosion/accretion patterns and the wave transformation mechanisms documented
813 by Iraqi (2008). These inferences require validation through direct sediment bud-
814 get calculations, bathymetric surveys, sediment tracer studies, or numerical sediment
815 transport modelling. The present study therefore identifies a plausible sediment-source
816 relationship rather than demonstrating a quantified sediment flux.

817
818
819 ***Extreme wave event declustering.***

820 The declustering of extreme wave events used a run length of 12 consecutive non-
821 exceedance observations, implemented as a row-based criterion rather than a strictly
822 hourly one. This approach was adopted because the merged ERA5–buoy record
823 contained small temporal gaps that precluded a strictly time-based run-length imple-
824 mentation. Accordingly, independent event counts should be interpreted as declustered
825 event clusters rather than strictly time-based independent events. This may affect
826 the identification of extreme wave events and the directional analysis associated with
827 them.

828

Spatial coverage and study design.

The shoreline analysis was focused on the central and northern sectors of Ras Al-Katib, encompassing approximately 5.6 km of the total 11 km barrier length, with transects generated at 100 m intervals. This spatial focus was a deliberate design choice, as these sectors exhibit the most pronounced and dynamically active shoreline changes, including the erosion hotspot in the central sector and the accretion zone at the northern end. The southern sector was not included in the analysis because it has historically shown lower rates of change and is less directly connected to the hydrodynamic processes that affect the navigation channel. Consequently, the findings and interpretations presented in this study are more representative of the central and northern sectors, and caution should be exercised when extrapolating the results to the entire barrier system without additional analysis.

5 Conclusions

1. This study provides a quantitative assessment of shoreline change along the analysed 5.6-km shoreline sector of the Ras Al-Katib coastal barrier in Hodeidah, Yemen, for the period 2000–2020 using DSAS. The analysis reveals a distinct spatial pattern: pronounced erosion in the central sector (maximum retreat of approximately 109 m; maximum rate of -5.5 m yr^{-1}) and significant accretion at the northern end (maximum advance of approximately 93 m; maximum rate of 4.66 m yr^{-1}).
2. ERA5 reanalysis data, validated against available in situ buoy observations, showed good agreement for significant wave height ($r = 0.831$, RMSE = 0.199 m, bias = +0.005 m) and reasonable directional agreement, with 80.3% of estimates within $\pm 45^\circ$ of buoy observations. However, ERA5 underestimated SWH during 94.3% of the declustered extreme-wave peaks, with a mean ERA5-to-buoy ratio of 0.706. No statistically significant long-term trend was detected in offshore SWH ($p = 0.898$) during 2001–2020. Directional analysis of the most energetic conditions (P95) revealed a highly concentrated southerly regime ($175.4^\circ \pm 6.5^\circ$), consistent with the winter hydrodynamic setting documented by Iraqi (2008) and the observed pattern of central erosion and northern accretion.
3. Although the meteorological and offshore wave analysis (2000–2020) indicates that regional mean temperature ($p = 0.450$) and average wave energy ($p = 0.898$) have remained statistically stable, these mean conditions cannot rule out hydrodynamic forcing as a primary driver of shoreline dynamics. Given that ERA5 systematically underestimates extreme peak wave heights by approximately 30%, episodic high-energy wave events are likely disproportionately important for sediment mobilisation relative to their frequency. Consequently, the observed spatial evolution of Ras Al-Katib is best understood as the combined result of mechanical forcing—driven by a pronounced seasonal reversal in wind direction (southerly in winter, north-westerly in summer) that generates highly directional energetic winter waves ($175.4^\circ \pm 6.5^\circ$)—nearshore wave transformation, and historical anthropogenic land-use modifications.

- 875 4. The observed sediment accumulation at the northern end of Ras Al-Katib has
876 potential implications for the adjacent Hodeidah navigation channel and naval base.
877 While a direct sediment budget is required to confirm this pathway, the spatial
878 and hydrodynamic connectivity between Ras Al-Katib and the navigation channel
879 suggests a plausible sediment source–sink relationship.
- 880 5. The findings underscore the need for integrated coastal monitoring and manage-
881 ment strategies in Yemen’s Red Sea coastal zone that account for both natural
882 hydrodynamic variability and anthropogenic pressures. Regular shoreline monitor-
883 ing using satellite imagery and DSAS, combined with wave climate assessment using
884 ERA5 or similar reanalysis products, can provide a cost-effective basis for adaptive
885 coastal management.

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