

Tracking Barchan Dune Migration Using Automated Analysis of Sentinel-1 SAR Imagery: Managing Aeolian Risk in Morocco's Southern Provinces

Suivi de la migration des barkhanes à l'aide de l'analyse automatisée d'images SAR Sentinel-1: gestion des risques éoliens dans les provinces du sud du Maroc

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Abstract. Monitoring the dynamics of barchan dunes is essential for understanding aeolian processes and anticipating their environmental and socio-economic impacts in arid regions. This study focuses on the Guerguerat dune field in southern Morocco, where active barchan dune migration poses potential risks to natural ecosystems and nearby infrastructure. To address this challenge, a semi-automated processing chain based on multi-temporal Sentinel-1 Synthetic Aperture Radar (SAR) imagery was developed. The workflow includes SAR preprocessing, speckle reduction, adaptive thresholding, and contour vectorization to extract dune geometries from three acquisition dates (2016, 2019, and 2022). Barchan dune displacement was then quantified using a centroid-matching approach to estimate migration rates and directions. The results indicate active barchan dune migration, with moderate mean velocities of approximately 49 m/yr for the 2016-2019 interval and 49 m/yr for 2019-2022. Migration rates show a strongly skewed distribution, with median values of ~53 m/yr and ~48 m/yr for the two sub-intervals, highlighting the influence of a subset of rapidly migrating dunes on short-term dynamics. Over longer timescales, migration appears more moderate, reflecting the smoothing effect of temporal averaging and the integration of alternating phases of high and low mobility. Migration directions are broadly consistent with the dominant south-southwest sediment transport associated with the prevailing regional wind regime, although local geomorphological and sedimentary constraints introduce spatial variability. Overall, these results demonstrate the potential of Sentinel-1 SAR amplitude data for robust and reproducible monitoring of dune dynamics, particularly in optically constrained environments. Beyond its methodological contribution, this study provides valuable insights into aeolian processes in hyper-arid regions and supports risk assessment and infrastructure planning in areas exposed to active barchan dune migration.

Keywords: Barchan dunes, Dune migration, Sentinel-1, Automated analysis, Wind, Morocco.

Résumé. Le suivi de la dynamique des dunes barkhanes est essentiel pour comprendre les processus éoliens et anticiper leurs impacts environnementaux et socio-économiques dans les régions arides. Cette étude se concentre sur le champ de dunes de Guerguerat, dans le sud du Maroc, où la migration active des barkhanes représente un risque potentiel pour les écosystèmes naturels et les infrastructures voisines. Pour répondre à cet enjeu, une chaîne de traitement semi-automatisée basée sur des images radar Sentinel-1 à ouverture synthétique (SAR) multi-temporelles a été développée. Le flux de travail comprend le prétraitement des images SAR, la réduction du chatoiement, un seuillage adaptatif et la vectorisation des contours afin d'extraire la géométrie des dunes à partir de trois dates d'acquisition (2016, 2019 et 2022). Le déplacement des barkhanes a ensuite été quantifié à l'aide d'une approche d'appariement des centroïdes afin d'estimer les vitesses et les directions de migration. Les résultats indiquent une migration active des barkhanes, avec des vitesses moyennes modérées d'environ 49 m/an pour la période 2016-2019 et de 49 m/an pour 2019-2022. Les vitesses de migration présentent une distribution fortement dissymétrique, avec des valeurs médianes d'environ 53 m/an et 48 m/an pour les deux sous-périodes, ce qui met en évidence l'influence d'un sous-ensemble de dunes à migration rapide sur la dynamique à court terme. À des échelles de temps plus longues, la migration apparaît plus modérée, reflétant l'effet de lissage de l'agrégation temporelle et l'intégration de phases alternées de forte et de faible mobilité. Les directions de migration sont globalement cohérentes avec le transport sédimentaire dominant orienté vers le sud-sud-ouest, associé au régime de vents régionaux, bien que des contraintes géomorphologiques et sédimentaires locales introduisent une variabilité spatiale. Dans l'ensemble, ces résultats démontrent le potentiel des données d'amplitude SAR Sentinel-1 pour un suivi robuste et reproductible de la dynamique des dunes, en particulier dans les environnements où les conditions optiques sont limitantes. Au-delà de son apport méthodologique, cette étude fournit des informations précieuses sur les processus éoliens en milieu hyper-aride et contribue à l'évaluation des risques et à la planification des infrastructures dans les zones exposées à la migration active des barkhanes.

Mots-clés : Barkhanes, Migration des dunes, Sentinel-1, Analyse automatisée, Vent; Maroc.

INTRODUCTION

The study of barchan dune dynamics has long represented a central topic in aeolian geomorphology, due to its implications for landscape evolution, desertification

processes, and human activities in arid environments. Among the various dune types, barchans attract particular interest because of their well-defined crescent-shaped morphology and their high mobility under the influence of unidirectional

wind regimes (Fig. 1). Early works, such as those by Long & Sharp (1964), provided pioneering quantitative data on dune migration, highlighting the role of sediment supply and morphology in controlling migration rates. Subsequent studies refined this understanding by linking barchan dune mobility to morphometric parameters and wind-sediment interactions, as observed along the Brazilian coast by Jiménez *et al.* (1999) and in Mauritania by Ould Ahmedou *et al.* (2007).

With the development of remote sensing, barchan dune monitoring methods gradually shifted from field-based surveys to satellite imagery. Early applications of radar data, notably in Kuwait (Kwarteng *et al.* 2000), demonstrated the potential of SAR imagery for accurate mapping of barchan dune morphologies in arid settings. More recently, the combined use of optical and radar platforms has enabled quantification of barchan dune kinematics across different spatial and temporal scales (Ali *et al.* 2020), providing detailed insights into migration rates and sediment fluxes. Parallel geomorphological research has also emphasized the role of airflow structures within interdune corridors in shaping barchan dune morphology and spacing (Baddock *et al.* 2006).

Over the past decade, machine learning and artificial intelligence have emerged as major methodological advances, offering promising perspectives for optimizing dune detection and monitoring. Recent approaches now integrate deep learning and multi-source imagery for the automated segmentation and classification of dune morphologies (Zhao *et al.* 2025), or for the detection and tracking of barchans on Earth and Mars (Cúñez & Franklin 2024). These methodological innovations not only enhance the precision of barchan dune field mapping but also open new avenues for long-term monitoring in the context of increasing climatic and anthropogenic pressures.

In this framework, the present study focuses on the dynamics of barchan dunes in the Guerguerat region of southern Morocco, using multi-temporal Sentinel-1 SAR imagery combined with semi-automated image processing techniques. The main objective is to quantify dune migration rates through contour extraction and centroid-based tracking, and to evaluate the performance of automated approaches for monitoring aeolian processes in hyper-arid environments.

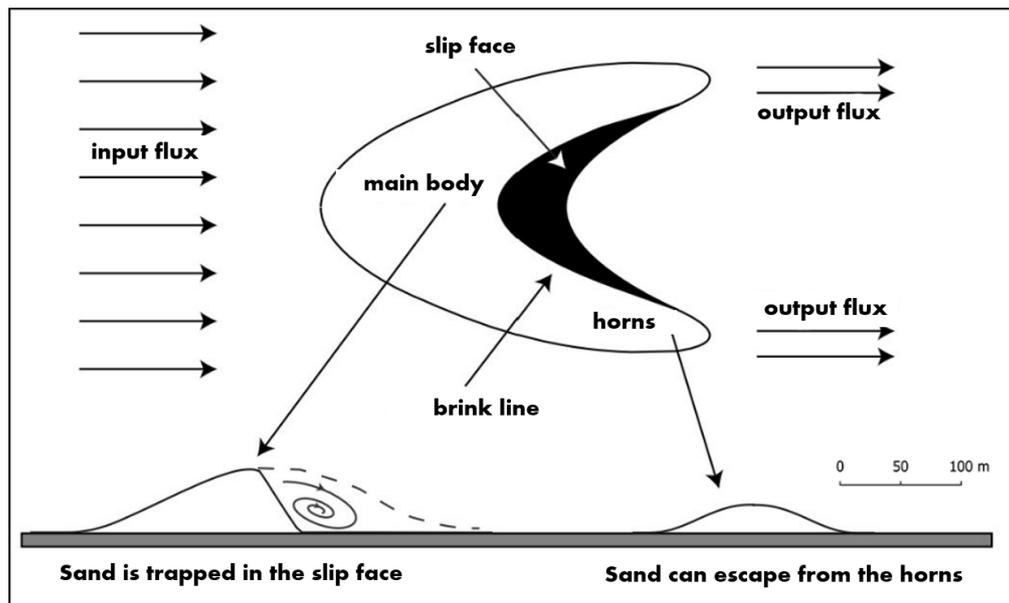


Figure 1. Morphology of barchan dunes. (Hersen, P. 2004).

MATERIALS

Study area

The study area is located in the extreme south of Morocco, within the Eddakhla-Oued Eddahab region, near the strategic border locality of Guerguerat (21°26'45.73"N, 16°51'21.71"W) (Fig. 2). This corridor represents the southernmost terrestrial connection between Morocco and Mauritania. The region is characterized by a large active barchan field (Fig. 2D). The proximity of migrating barchans makes this area particularly sensitive: several barchan dunes are located directly under the dominant wind influence, where persistent trade winds promote continuous south-southwest sand displacement. Episodes of rapid barchan dune encroachment have already been observed in the area. These conditions justify the selection of Guerguerat as a case study, as it represents a real hotspot of aeolian dynamics characterized by high dune mobility (Fig. 2B-C).

Climatically, the region is dominated by arid to hyper-arid conditions, with mean annual precipitation generally below 50 mm and subject to high interannual variability. Temperatures exhibit pronounced diurnal and seasonal contrasts, while surface winds, predominantly driven by persistent northeast trade winds, are strong and largely unidirectional. Such conditions foster aeolian transport and sustain the continuous migration of barchans.

The geological substrate exerts a major control on barchan dune dynamics. It is primarily composed of Precambrian metamorphic and magmatic formations, including gneisses, granites, and schists (Michard *et al.* 2008). The weathering of these lithologies, modulated by sediment availability, grain size, and regional topography, supplies the sandy reservoirs that maintain the dune system. Consequently, the morphology, distribution, and mobility of barchans are directly influenced by these geological and geomorphological factors (Elbelrhiti 2012).

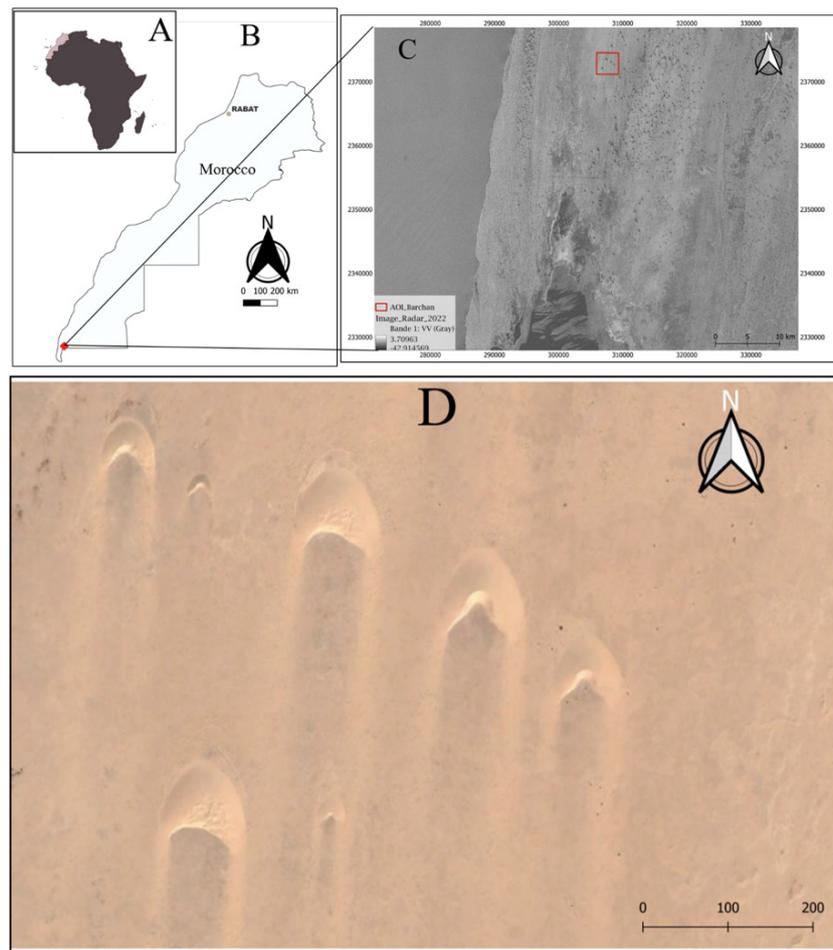


Figure 2. Study area and multi-scale mapping of the Guerguerat corridor (Location of Morocco in Africa (A); Regional setting of the study area (B); SAR image of the Guerguerat barchan dune field (C); Optical view of the barchan dunes (D)).

Data Acquisition

Sentinel-1 radar images obtained from the Copernicus Open Access Hub were used to analyse the dynamics of barchan dunes. Three Level-1 Ground Range Detected (GRD) images acquired in 2016, 2019, and 2022 were selected based on strict quality and comparability criteria. These acquisition dates were chosen to ensure a temporal baseline long enough for dune displacements to exceed positional uncertainties, while maintaining optimal radiometric quality and geometric consistency across the dataset. They correspond to the most radiometrically and geometrically stable acquisitions over the 2016-2022 period, as several other images exhibited edge effects, increased thermal noise, or reduced contrast associated with the low backscatter of the local lithology.

All three selected scenes were acquired under identical conditions, namely an ascending orbit, VV polarization, and an incidence angle of approximately 39° , thereby ensuring a consistent observation geometry and minimizing interannual acquisition biases. The choice of a regular three-year interval provides sufficiently long periods for measurable dune displacements to emerge beyond sub-pixel uncertainties, while avoiding redundancy and excessive noise that may result from the use of intermediate acquisitions associated with limited displacement.

The use of SAR amplitude imagery is motivated by its suitability for monitoring barchan dune fields characterized by high surface variability and continuous morphological evolution. In sandy desert environments, Sentinel-1 C-band

SAR data exhibit strong sensitivity to variations in surface roughness and micro-topography, allowing reliable delineation of dune crests, slip faces, and interdune areas, independently of illumination conditions and atmospheric effects (Emran *et al.* 2020). These properties make SAR amplitude data particularly well suited for extracting dune geometries and quantifying barchan dune displacement.

Wind Data

Wind data for the study area were obtained from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Hourly wind components at 10 m height (u_{10} and v_{10}) were extracted over the Guerguerat dune field for the period 2016-2022. ERA5 provides a physically consistent and temporally continuous description of atmospheric conditions, making it well suited for characterizing regional wind regimes driving aeolian processes in hyper-arid environments.

To ensure consistency with the dune migration analysis, wind statistics were evaluated over the same temporal windows used for displacement measurements, namely 2016-2019 and 2019-2022. Aligning wind data with the Sentinel-1 acquisition intervals allows aeolian forcing to be examined over time spans directly comparable to the observed geomorphological changes. The use of multi-year intervals further reduces the influence of short-term atmospheric variability and provides a more robust representation of the dominant regional wind regime.

Wind speed was computed from the horizontal wind components, and wind direction was derived following standard meteorological conventions. Wind variability and directional characteristics were analysed using monthly wind speed distributions and directional diagrams (Fig. 3), which provide a direct and physically meaningful representation of the temporal and directional structure of the aeolian forcing. These graphical representations facilitate the identification of dominant wind regimes and seasonal variability, thereby supporting subsequent analyses of dune orientation and migration patterns.

METHODOLOGY

Our methodology to identify and detect barchan dune using SAR imagery is structured into five steps (Fig. 4): (1) Data collection, (2) preprocessing of Sentinel-1 SAR data and segmentation, (3) thresholding and contour extraction, (4) morphometric characterization, (5) multi-temporal displacement analysis, and (6) correlation with wind forcing.

SAR Data Preprocessing

The preprocessing of Sentinel-1 C-band SAR imagery (acquired in 2016, 2019, and 2022) was designed to optimize the detectability and morphometric delineation of barchan dunes under conditions of strong speckle contamination and radiometric heterogeneity. The processing workflow was implemented in Python, using the Roserio, NumPy, SciPy, and Scikit-image libraries, which guarantees full reproducibility of the steps.

Missing or undefined pixel values were first corrected to avoid anomalous discontinuities during subsequent filtering and segmentation steps. Speckle suppression was achieved by applying a Gaussian filter ($\sigma = 1$), which acts as a localized isotropic convolution kernel. Unlike boxcar smoothing, the Gaussian kernel assigns greater weight to central pixels while progressively down-weighting neighbours, thereby attenuating stochastic high-frequency noise while preserving sharp backscatter discontinuities corresponding to dune

crests and steep slopes. Radiometric enhancement was performed through a percentile-based histogram stretch (2nd-98th percentiles), redistributing intensity values across the full dynamic range and increasing local contrast between dune bodies and the surrounding interdune substrate. This step improved separability in areas where subtle variations in soil roughness and moisture could otherwise obscure dune signatures. To ensure temporal comparability, all pre-processed images were normalized on a [0-1] scale, reducing the influence of acquisition-specific radiometric biases and guaranteeing consistency in multi-date analyses (Fig. 5).

Segmentation was carried out using a dual thresholding approach. Adaptive local thresholding, based on sliding-window statistics (block size = 35 pixels, offset = 0.02), was employed to incorporate spatial variability in backscatter intensity. This method is particularly suited to arid regions where radar returns fluctuate with surface roughness, sediment supply, and microtopography. For validation, Otsu's global thresholding criterion (Otsu 1979) was applied in parallel, ensuring that the extracted binary masks remained robust against global intensity variations. These binary outputs (Fig. 6) enabled a reliable separation between dune and non-dune classes. From these masks, isocontour extraction and polygonization were performed, followed by reprojection into a UTM metric coordinate system (EPSG: 32629) to enable morphometric calculations.

Contour Extraction and Vectorization

Following binary segmentation, barchan dune boundaries were extracted and converted into georeferenced vector objects to enable morphometric and spatio-temporal analyses. The processing workflow relied on isocontour extraction applied at the 0.5 threshold level of the binary raster, ensuring precise delineation of transitions between the foreground (dune) and the background (substrate). To minimize noise and spurious detections, contours smaller than 20 pixels (corresponding to approximately 2000 m² at 10 m spatial resolution) were automatically discarded.

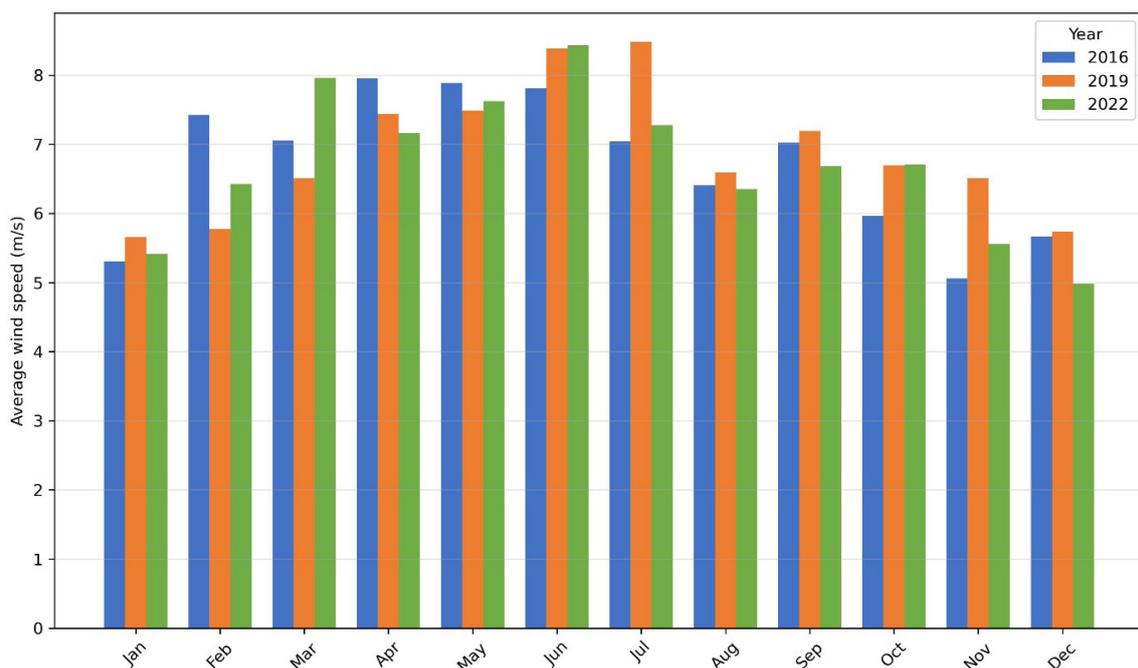


Figure 3. Monthly variability of mean wind speed at 10 m height derived from ERA5 over the Guerguerat dune field (2016, 2019, and 2022).

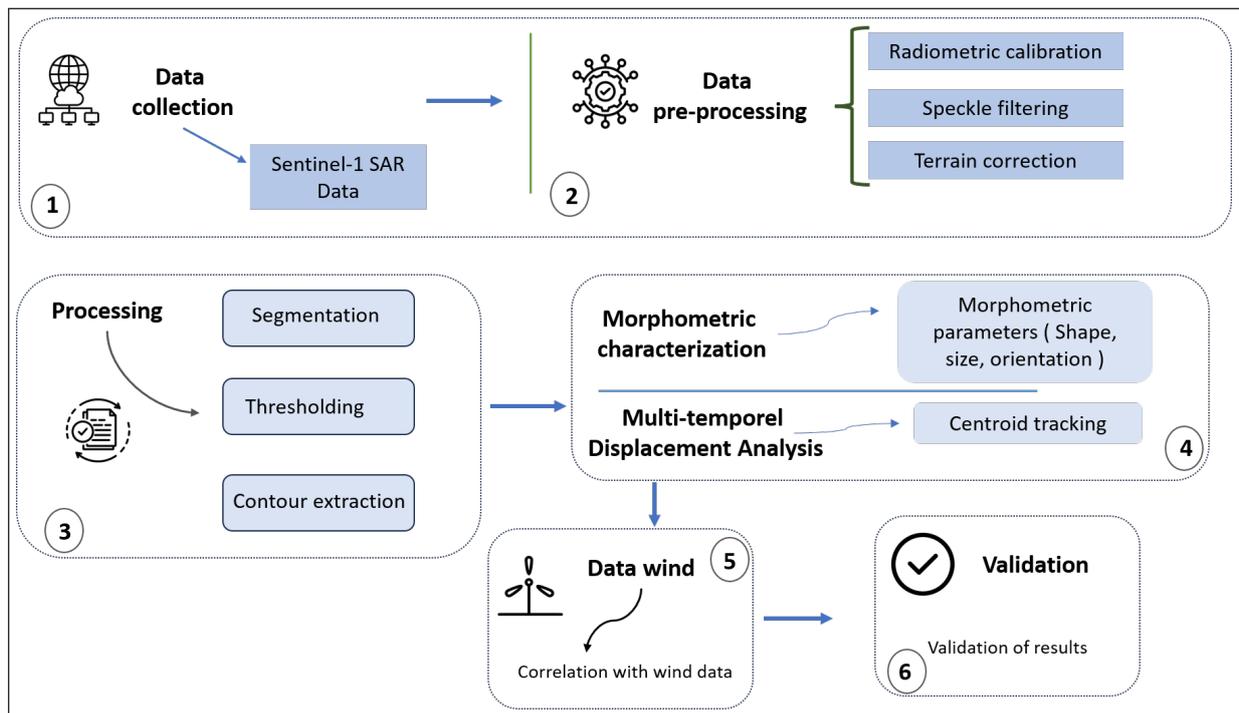


Figure 4. Methodology overview.

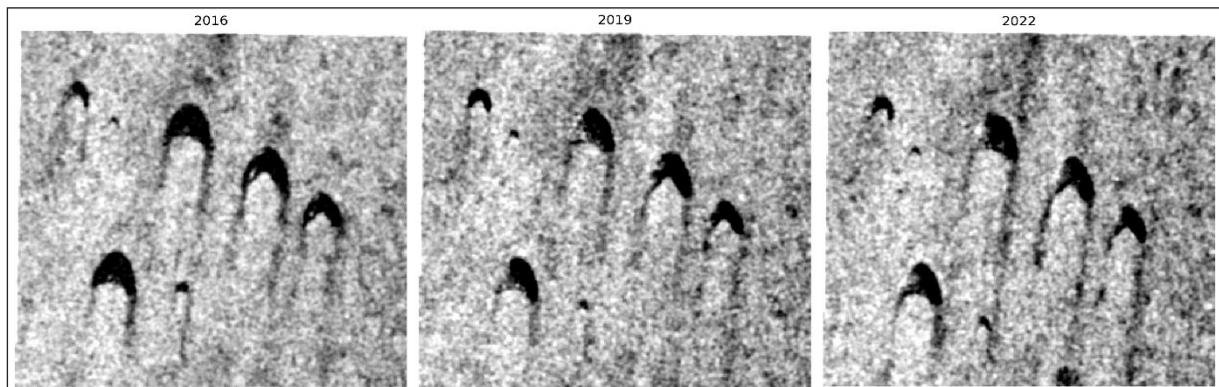


Figure 5. Pre-processed Sentinel-1 C-band SAR images of the Guerguerat barchans for 2016 (left), 2019 (center), and 2022 (right).

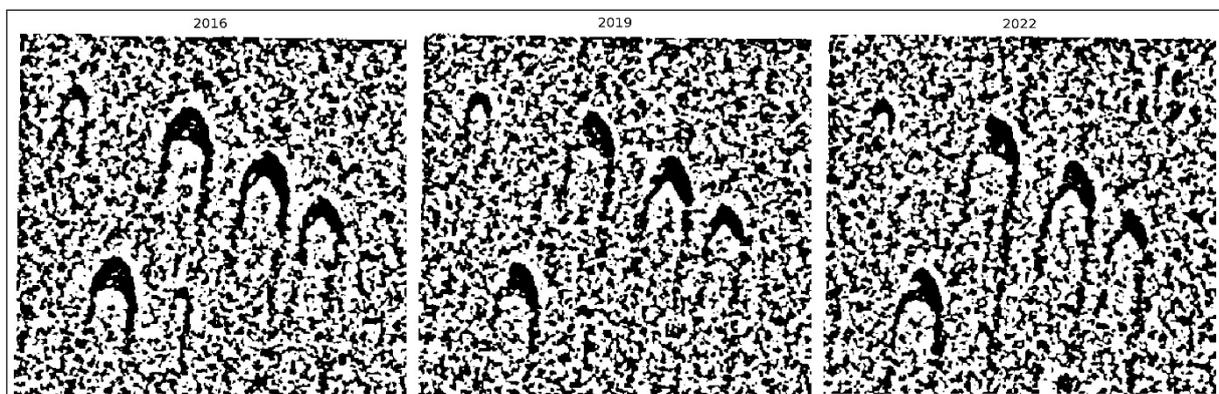


Figure 6. Binary segmentation masks of barchan dunes derived from Sentinel-1 SAR imagery for 2016 (left), 2019 (center), and 2022 (right).

Each valid contour was subsequently transformed into a closed polygon through the raster-to-vector conversion procedure, in which pixel coordinates were mapped into geographic space via the affine transformation of the original Sentinel-1 dataset. The resulting polygons were geometrically validated, and topological errors, such as residual fragments or self-intersections, were corrected using a zero-distance buffer. Additional quality filters were applied, retaining only dunes with a surface area greater than 2000 m² and a compactness index above 0.85, thereby ensuring a dataset limited to morphologically robust entities. The validated barchan dune contours were then reprojected into the UTM coordinate system (Zone 28N; EPSG:32628), allowing surface, distance, and orientation measurements to be expressed in metric units. This procedure produced a coherent geospatial dataset composed of vectorized dune polygons for the three acquisition dates, thereby facilitating morphometric characterization and multi-temporal displacement analysis.

Morphometric Characterization of Barchans

Each validated barchan dune polygon was characterized using a comprehensive set of morphometric descriptors designed to quantify geometry, elongation, and orientation. Barchan dune surface area was calculated directly from polygon geometry, while length (L) and width (W) were derived from the minimum bounding rectangle. Orientation was defined as the azimuth of the rectangle's long axis relative to geographic north, thereby providing a robust measure of crest alignment. Additional descriptors included the aspect ratio (L/W), convex hull extension (maximum dune diameter), and centroid coordinates, which served as unique spatial identifiers for subsequent displacement analyses.

To ensure data reliability, only barchan dunes with a surface area greater than 200 m² and a compactness index above 0.85 were retained, thereby eliminating spurious polygons generated by speckle noise. This filtering criterion ensured that morphometric statistics reflected actual dune forms rather than segmentation artifacts. Such an approach is consistent with methodological standards in aeolian geomorphology, where the exclusion of small or irregular polygons is essential to guarantee meaningful comparisons across temporal datasets.

These morphometric descriptors provide a quantitative basis for evaluating spatio-temporal variability within the dune field. They enable investigation of relationships between barchan dune size, shape, and orientation, as well as their potential links to external forcing factors. By standardizing this set of descriptors across the three acquisition dates, a reproducible framework is established for monitoring morphological changes over time.

Multi-Temporal Displacement Analysis

The quantification of barchan dune mobility was performed by tracking the displacement of barchan dune centroids across multi-date datasets. A nearest-neighbour association algorithm was implemented to establish correspondence between barchans, applying constraints on spatial proximity and morphological similarity. Specifically, centroid matching was restricted to a maximum search radius to account for plausible migration distances, while an area ratio criterion was applied to ensure consistency in barchan dune size across acquisitions, in line with approaches widely used in barchan dune migration studies (Vermeesch 2011, Cúñez & Franklin 2024). For each validated pair, displacement vectors

were derived from centroid coordinates, expressed in both magnitude and azimuth. These vectors were subsequently normalized by the acquisition interval to compute annual migration rates, thereby providing a standardized indicator of barchan dune mobility across different temporal scales.

To assess the role of atmospheric forcing, the displacement vectors were compared with wind data extracted from the ERA5 reanalysis dataset at 10 m height. Monthly time series of wind speed and direction were aggregated using cubic weighting (U³), reflecting the nonlinear dependence of aeolian sand transport on wind velocity (Bagnold 1941, Sherman *et al.* 2025). This weighting approach emphasizes the disproportionate contribution of high-intensity wind events to sediment transport and barchan dune migration, in accordance with established aeolian transport theory (Livingstone & Warren 1996). The prevailing wind transport vectors derived from ERA5 were then used as a reference against which barchan dune migration trajectories were compared. For each dune, the angular deviation between the observed displacement direction and the dominant wind direction was calculated, and the wind-aligned component of migration was extracted. This analysis allows an assessment of the degree of alignment between barchan dune displacement and regional wind forcing, while accounting for potential local geomorphological or sedimentary influences (Courrech du Pont *et al.*, 2014). This integrative approach, combining automated SAR-based displacement tracking with ERA5 wind climatologies, provides a robust framework for distinguishing the respective influences of regional atmospheric forcing and local geomorphological factors on barchan dune dynamics.

RESULTS AND DISCUSSION

Migration Dynamics of Barchan Dunes

The analysis of barchan dune migration dynamics highlights a marked variability across the investigated temporal intervals. The multi-temporal superposition of barchan dune contours (Fig. 7) provides a direct spatial visualization of dune displacement between 2016, 2019, and 2022, illustrating both the consistency of migration directions and the variability in displacement magnitudes among individual dunes. This spatial organization is supported by the migration speed histograms (Fig. 8) and the comparative boxplot (Fig. 9).

During the short-term periods (2016-2019 and 2019-2022), barchan dunes exhibit relatively high migration rates, with mean migration speeds of 49.0 m/yr and 48.8 m/yr, respectively. These values indicate an active dune mobility at interannual time scales.

Over the entire 2016-2022 period, the mean migration speed decreases to 29.4 m/yr, reflecting a more moderate overall mobility when barchan dune displacement is evaluated over longer time scales and highlighting the smoothing effect associated with long-term temporal integration.

Influence of Wind Forcing on Dune Migration

The analysis of wind influence on barchan dune mobility reveals a strong relationship between the dominant wind regime and the orientation of barchan dunes. Wind data indicate a persistent transport direction toward the south-southwest, with mean transport directions consistently centered around the SSW sector throughout the study period. This stability in wind direction provides a consistent atmospheric forcing capable of shaping dune morphology at the field scale.

A comparison between dune orientation and wind direction shows a high degree of agreement, as evidenced by a strong positive correlation coefficient of approximately $r = 0.79$. This result indicates that the orientation and crescentic geometry of barchan dunes are largely controlled by the prevailing wind regime. The close correspondence between wind direction and dune alignment highlights the dominant role of atmospheric forcing in organizing the spatial structure of the Guerguerat dune field.

This directional control is further illustrated by the comparison between transport-weighted wind roses (Fig. 10) and barchan dune orientation rose (Fig. 11), which both display a clear preferential alignment consistent with the dominant south-southwest wind regime. While some dispersion in barchan dune orientation is observed, likely reflecting local-scale interactions such as dune-dune collisions, sediment redistribution, and surface heterogeneities, the overall organization of the dune field remains strongly governed by regional wind forcing.

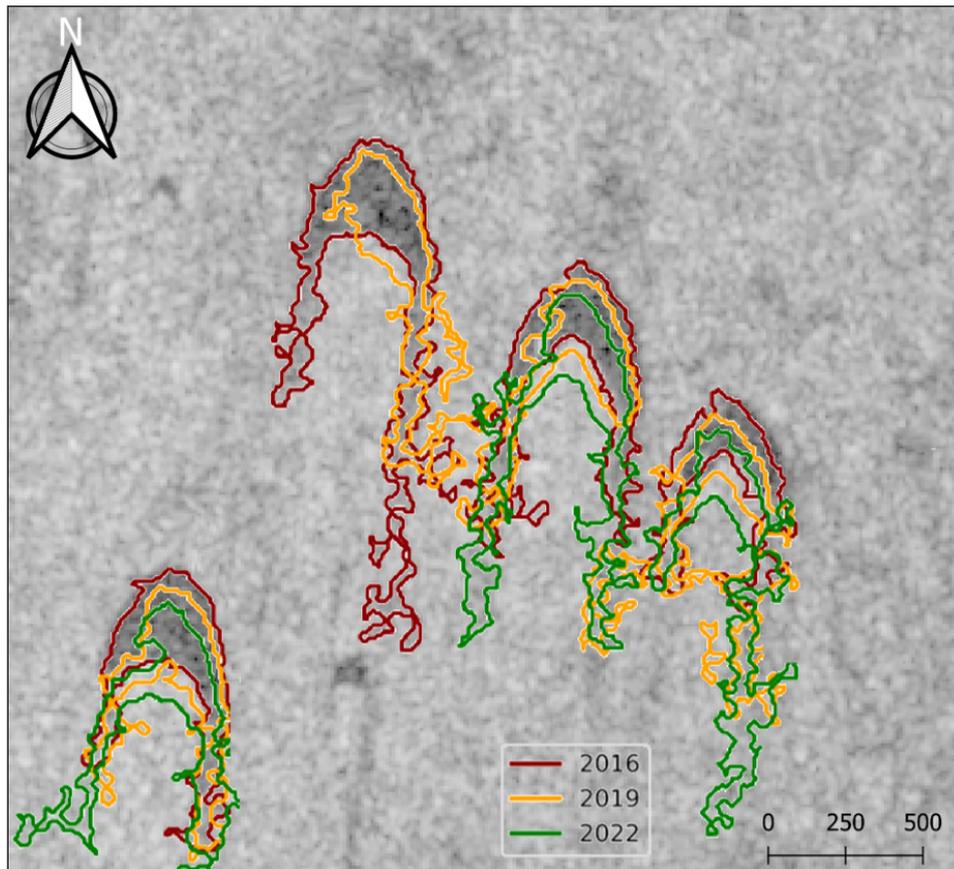


Figure 7. Visualization of major barchan dune contour displacement from 2016 to 2022.

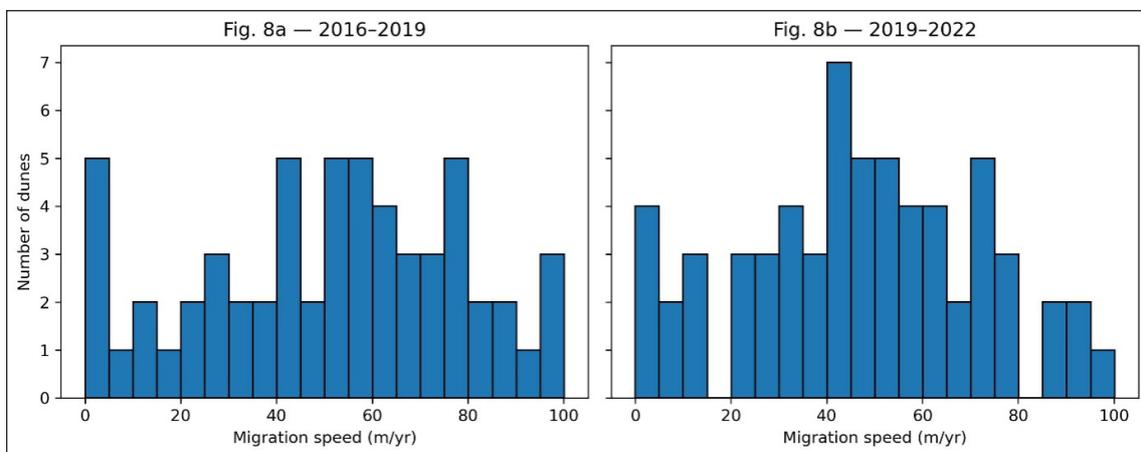


Figure 8. Distribution of all barchan dunes migration speeds across different temporal intervals: (a) 2016-2019 and (b) 2019-2022.

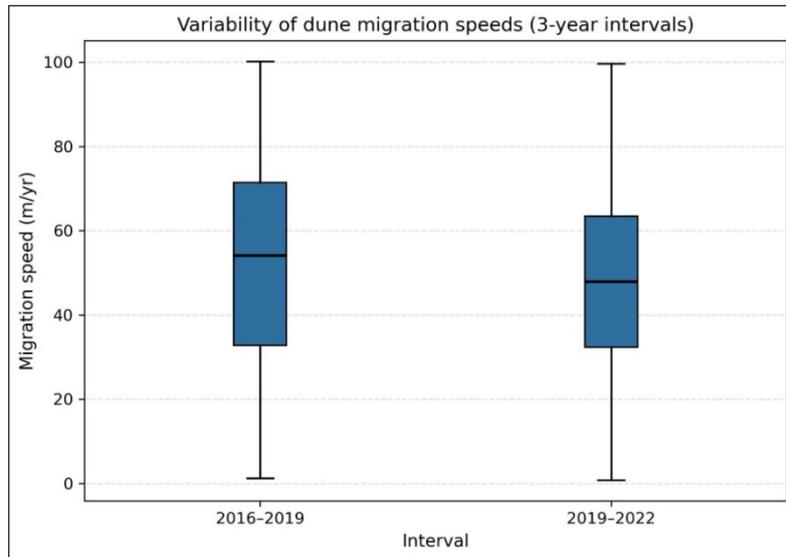
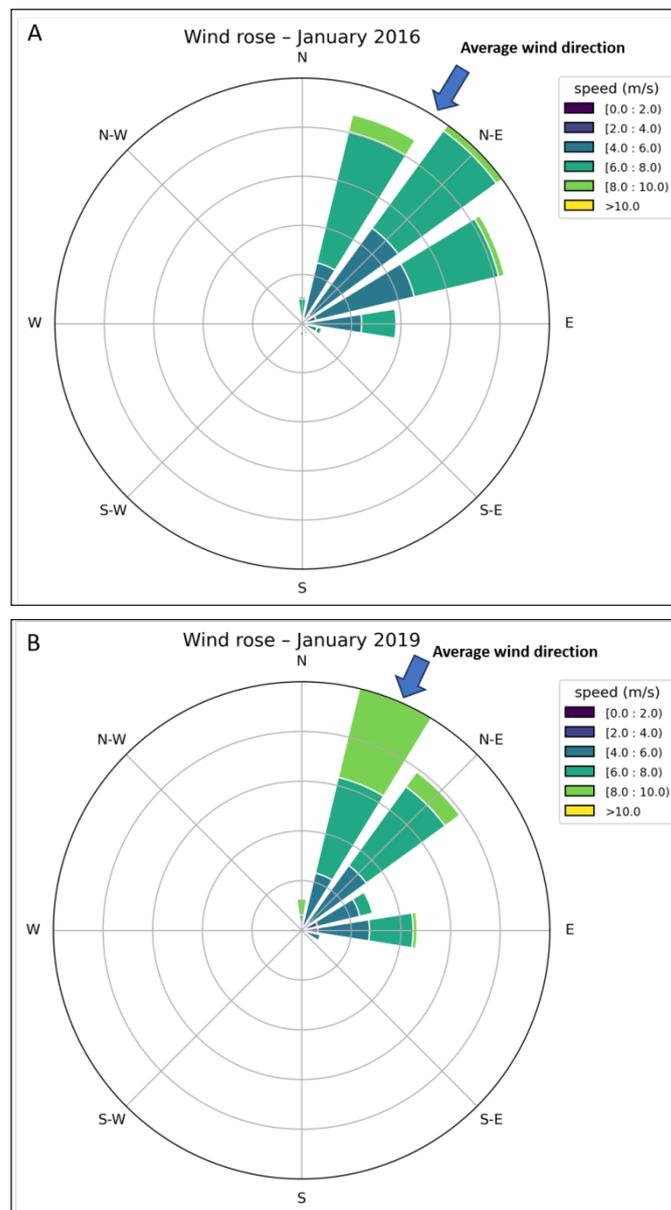


Figure 9. Variability of all barchan dunes migration speeds across different temporal intervals (2016-2019 and 2019-2022).



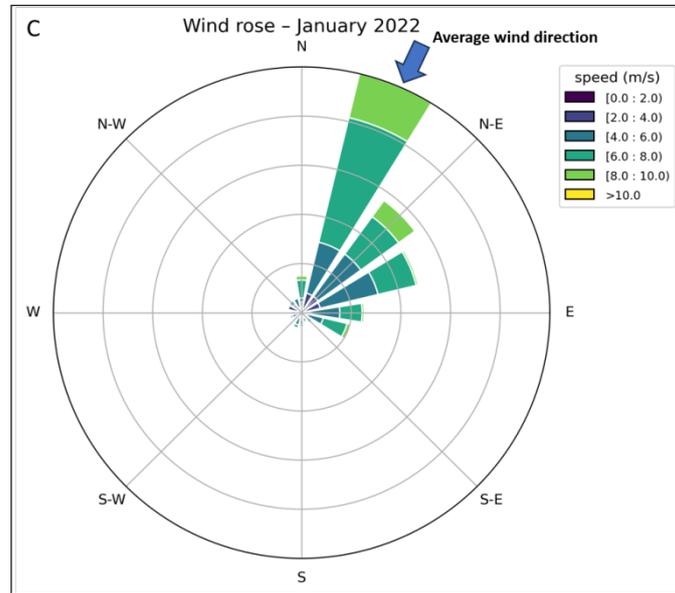


Figure 10. Wind roses derived from ERA5 reanalysis for January 2016 (A), 2019 (B), and 2022 (C).

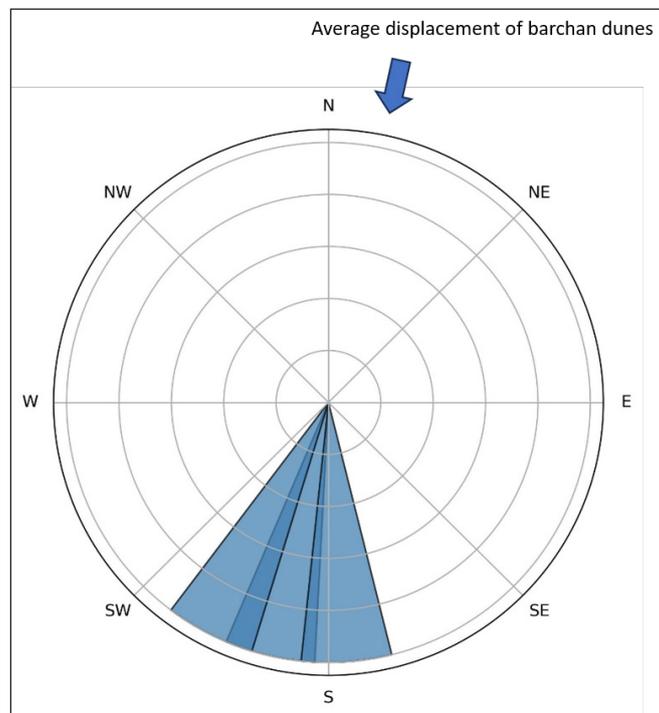


Figure 11. Orientation rose of barchan dunes (2016-2022).

The strength of this relationship is quantitatively confirmed by the correlation analysis between mean barchan dune orientation and wind direction (Fig. 12). Despite the limited interannual variability in wind direction, the observed correlation demonstrates that even subtle changes in atmospheric forcing are reflected in the mean orientation of barchan dunes. These results emphasize that, in the Guerguerat region, wind exerts a primary and persistent control on barchan dune orientation, providing a stable directional framework within which local geomorphological processes modulate barchan migration pathways.

Mechanisms of Barchan Formation and Evolution

The dynamics observed in the Guerguerat dune field can be better understood by considering the fundamental mechanisms governing the formation and evolution of barchan dunes. These barchans typically develop under persistent unidirectional wind regimes, limited sand supply, and relatively resistant substrates. Sediment is entrained on the stoss slope, transported across the crest, and subsequently avalanches down the slip face, ensuring the continuous forward migration of the dune body. Consistent with classical aeolian theory, barchan dune migration velocity is generally described as inversely proportional to dune size, with smaller dunes migrating more rapidly due to their limited sediment volume and lower inertia, whereas larger dunes tend to migrate more slowly (Livingstone & Warren, 1996). In Guerguerat, the persistence of trade winds blowing predominantly from the north-northeast provides a stable atmospheric forcing that strongly controls dune orientation and maintains the characteristic crescentic morphology of barchans. However, despite this clear directional control, the weak statistical relationship between wind forcing and migration rates highlights the importance of local-scale processes in modulating barchan dune displacement. Dune-dune

interactions, sediment exchanges, and spatial heterogeneities in surface conditions (such as moisture, roughness, and microtopography) contribute to deviations from strictly wind-aligned migration paths and to the pronounced variability in migration speeds observed within the field (Courrech du Pont *et al.* 2014).

The observed reduction in the number of individual dunes between 2016 and 2022, together with the applied filtering criteria, suggests that coalescence and extinction processes are actively shaping the barchan dune field. Smaller and more mobile dunes are progressively absorbed by larger forms or disappear altogether, leading to a gradual reorganization of the barchan dune population. Such behavior is consistent with self-organization mechanisms documented in both Saharan and extra-Saharan dune systems, where barchan dune fields evolve through interactions, merging events, and selective survival of more stable barchan dune forms (Durán & Herrmann 2006, Elbelrhiti *et al.* 2015).

Comparison with Previous Studies

The migration rates documented in Guerguerat (~15-25 m/yr for most barchan dunes, with peaks exceeding 50 m/yr) are broadly consistent with findings from other barchan dune fields. Elbelrhiti *et al.* (2015) reported migration rates of 10-20 m/yr in Moroccan dune fields, values comparable to the medians observed in this study. The relatively weak relationship between wind forcing and barchan dune migration in Guerguerat contrasts with results from more homogeneous dune fields (Courrech du Pont *et al.* 2014), where stronger directional alignment is generally observed. This divergence highlights the importance of geomorphological heterogeneity and local sedimentary constraints in modulating dune responses to wind. The progressive reduction in barchan dune number further supports theoretical models of dune field self-organization (Durán & Herrmann 2006), in which coalescence

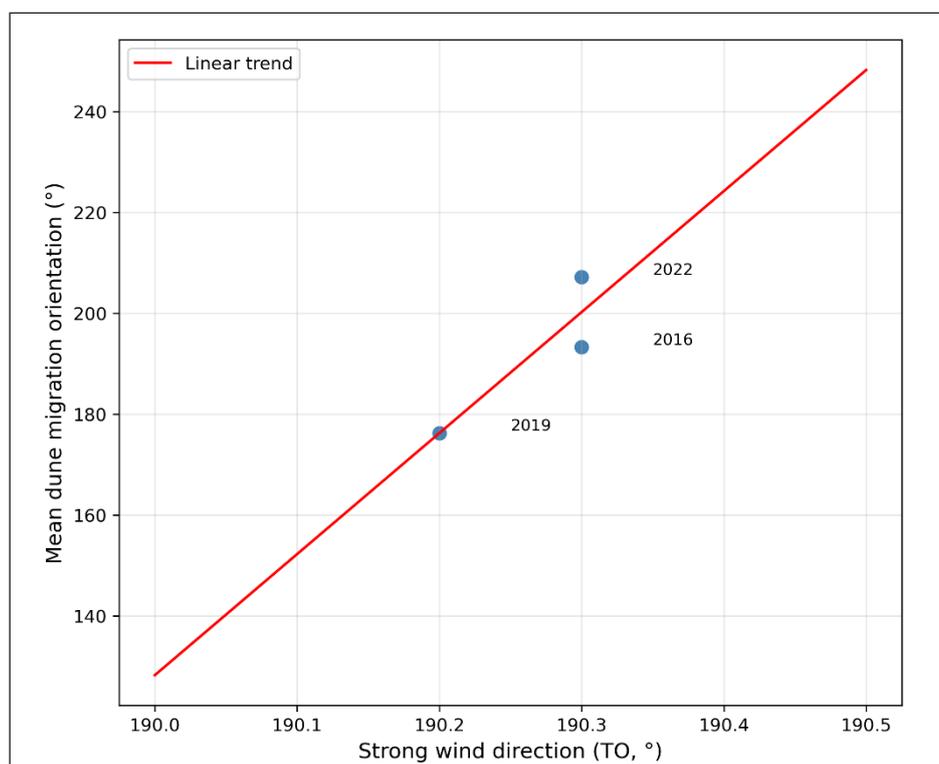


Figure 12. Correlation between barchan dunes orientation and strong wind direction.

and extinction emerge as natural adjustment mechanisms governing the long-term evolution of dune systems.

Synthesis and Implications

Overall, the Guerguerat barchan dune field exhibits dynamics that are broadly comparable to those observed in other Saharan and global desert systems. Barchan dune migration remains active and spatially variable, with short-term displacement rates reflecting episodic wind forcing, while longer-term trends reveal more moderate and stabilized migration behavior. Although the prevailing wind regime exerts a strong control on barchan dune orientation, migration rates are significantly modulated by local morphodynamic interactions, including dune-dune collisions, sediment redistribution, and surface heterogeneities, as well as by field-scale self-organization processes.

From a methodological perspective, this study demonstrates that the integration of multi-temporal Sentinel-1 SAR imagery with a semi-automated processing provides a robust and reproducible framework for monitoring barchan dune dynamics, while requiring fewer training data and assumptions than approaches relying exclusively on machine learning or deep learning techniques. Recent studies have shown that deep learning networks can substantially enhance dune segmentation and morphological classification from multi-source imagery (Zhao *et al.* 2025); however, the approach adopted here offers an efficient alternative for large-scale and long-term monitoring using freely available SAR archives.

The results further highlight the importance of such monitoring for assessing and anticipating the risks posed by migrating barchans to infrastructure and transportation corridors in southern Morocco. By capturing both the directional control imposed by regional wind forcing and the variability introduced by local processes, the developed framework underscores the value of radar remote sensing for building predictive models of dune field evolution under different climatic scenarios. Future research should aim to integrate three-dimensional metrics, digital elevation models, and interferometric techniques, together with systematic field surveys, in order to further improve both the scientific understanding of aeolian dynamics and the practical capacity to anticipate environmental hazards in hyper-arid landscapes.

CONCLUSION

This study provides new insights into the morpho-dynamics of barchan dunes in the Guerguerat region of southern Morocco by combining multi-temporal SAR imagery with semi-automated processing and morphometric analyses. The results reveal a wide variability in dune migration behavior, with most dunes exhibiting moderate displacement rates, while a smaller fraction displays significantly higher velocities, leading to asymmetric and skewed distributions of migration speeds. Temporal changes in barchan dune abundance over the study period further suggest the occurrence of self-organization processes within the dune field.

The analysis confirms that wind forcing is the primary driver of dune mobility in the study area, as evidenced by a strong positive correlation between wind direction and barchan dune orientation ($r = 0.79$). This result highlights the dominant role of regional atmospheric forcing in controlling barchan displacement under the relatively homogeneous climatic conditions of the Guerguerat region. At the same time, the observed dispersion around this relationship

indicates that local controls, including dune size, sediment availability, surface conditions, and dune-dune interactions, modulate the response of individual dunes, contributing to the overall variability of migration behavior. These findings underscore the heterogeneous and nonlinear nature of dune responses in hyper-arid environments.

Beyond the empirical observations, this work demonstrates the relevance of semi-automated approaches for dune monitoring, including automated contour extraction, morphometric characterization, and centroid-based tracking. These methods reduce operator subjectivity and enable consistent long-term analyses using freely available SAR archives. The integration of machine-learning assisted techniques illustrates the ongoing evolution of remote sensing workflows toward more robust, reproducible, and scalable frameworks for aeolian studies.

Future research should prioritize the integration of complementary three-dimensional information derived from digital elevation models and repeated topographic surveys, combined with systematic field validation, to better constrain volumetric changes and sediment fluxes. Given the rapidly changing surface properties of active dunes, classical radar interferometry remains challenging in such environments; therefore, alternative approaches better suited to highly dynamic sandy surfaces should be further explored. In addition, coupling SAR-derived indicators with predictive models under different climatic scenarios would improve our capacity to anticipate dune field evolution and associated environmental risks. In summary, this study advances the understanding of barchan dune dynamics in hyper-arid regions and highlights the strong potential of SAR-based and machine-learning assisted approaches as effective tools for monitoring and interpreting aeolian processes at regional scales.

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