Alongshore Varying Dune Retreat at Barrier Island

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INTRODUCTION

Figure 1. Study site: Culatra Island, Portugal.Sediment-starved west (erosion), accreting east (growth onto ebb-tidal delta).Waves predominantly from W–SW, tides ~2.8 m range.

Culatra Island presents a natural laboratory of alongshore variability, with a sediment-starved west end (due to jetty-induced blockage) and an accreting east end (fed by Armona Inlet's ebb-tidal delta). This spatial heterogeneity in sediment supply, wave exposure, and dune elevation sets the stage for differential coastal responses to storm events.

The objective is to simulate the alongshore variability due to longshore transport gradients and cross-shore fluxes by dune interactions.

DISCUSSION

To simulate storm-driven shoreline and dune evolution at Culatra Island, we coupled the ShorelineS one-line shoreline model with an impact-based dune erosion module, dynamically forced by nearshore wave conditions transformed by SnapWave. Corrected ERA5 offshore wave data were propagated to ~400 m offshore points, accurately representing alongshore wave energy gradients. Thirty-one clustered storm events were extracted from 2009–2011 based on significant wave height thresholds and storm duration criteria for correlation analysis against dune retreat. The model successfully reproduced key patterns of shoreline and dune changes across the island, including westward erosion, eastward accretion, and the emergence of dune erosion hotspots. Validation against satellite-derived shoreline positions and NDVI-based dune vegetation lines demonstrated good agreement ($R^2 \approx 0.59$ for dune retreat). However, shoreline change was slightly overestimated, with greater-than-observed accretion in the east and erosion in the west, reflecting limitations in representing detailed longshore sediment gradients within the one-line approach. Cumulative sediment flux during storms and storm duration emerged as the key drivers of dune retreat.

CONCLUSIONS

The coupled shoreline–dune modeling framework successfully captured the alongshore variability in shoreline and dune responses to longshore gradients and cross-shore cumulative storm impacts. A pronounced erosion hotspot was identified between T42–T77, where repeated dune retreat altered the adjacent shoreline morphology. The integration of SnapWave-transformed nearshore wave conditions significantly improved the accuracy of model forcing. Validation against NDVI-derived vegetation lines and satellite shoreline positions confirmed the model's ability to reproduce observed patterns, demonstrating the value of combining nearshore wave modeling with simple 1D shore and dune erosion modules

METHODS

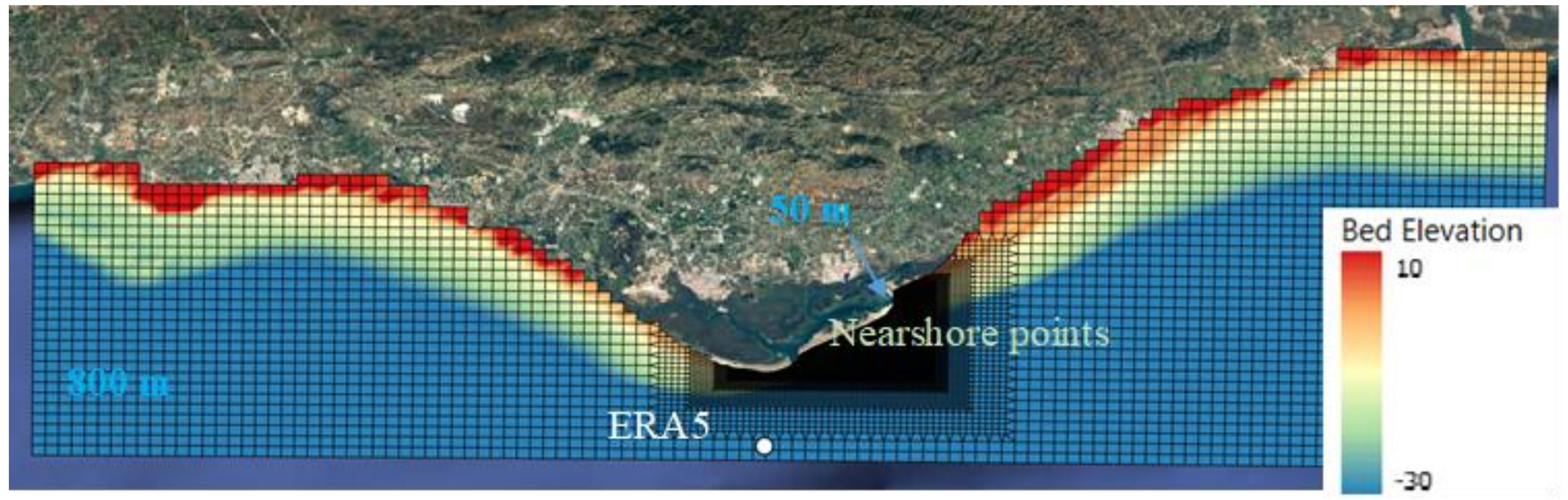

Figure 2: SnapWave nearshore wave grid and observation points (~400 m from shoreline). Corrected ERA5 wave conditions were transformed to accurately represent spatial variations in wave energy, providing realistic inputs for shoreline and dune evolution modeling.

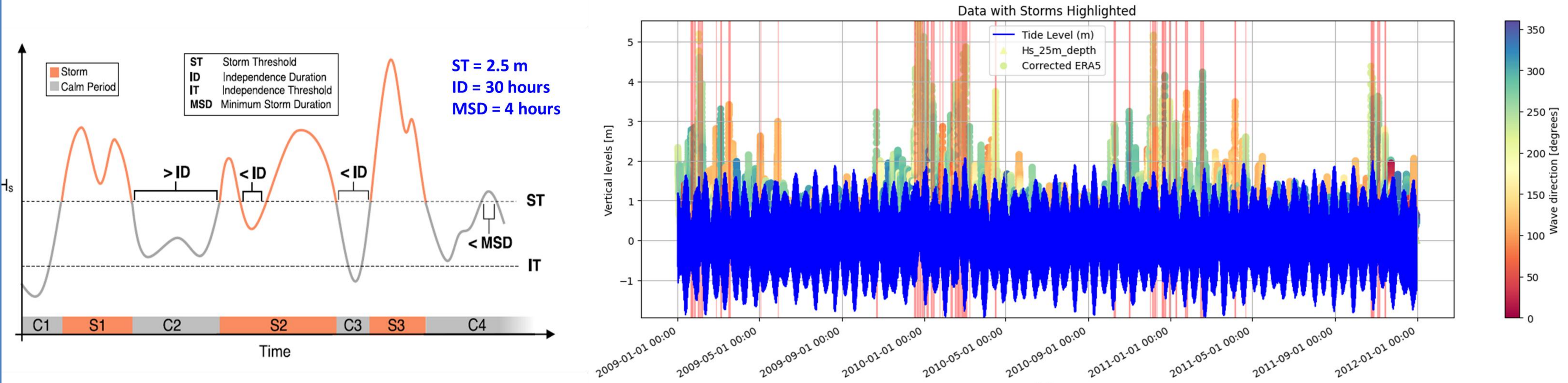

Figure 3. Time series of significant wave height (Hs) showing storm event identification (Hs > 2.5 m for >4 hours) during 2009–2011. Thirty-one clustered storms were extracted for coastal impact analysis. (Kumerrer et al., 2023)

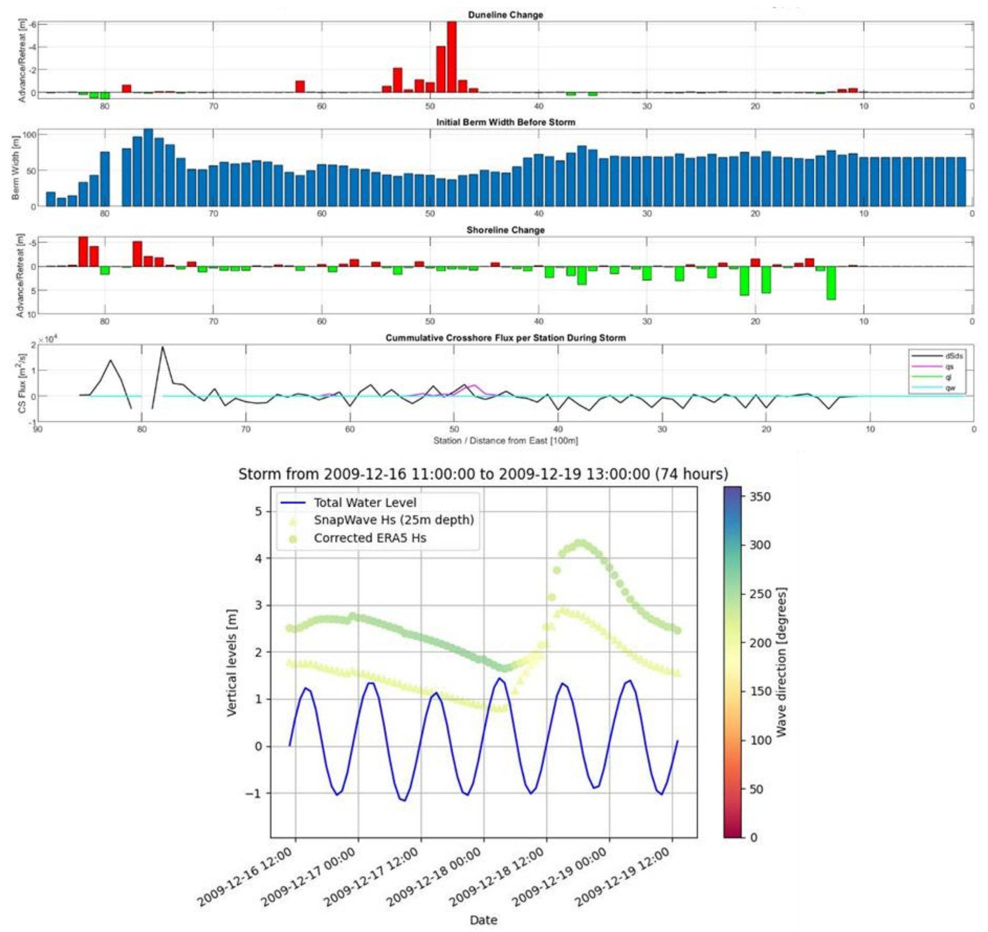

Figure 4. Extracted storm parameters, including cumulative sediment transport and storm duration, used for correlation with shoreline and dune evolution.

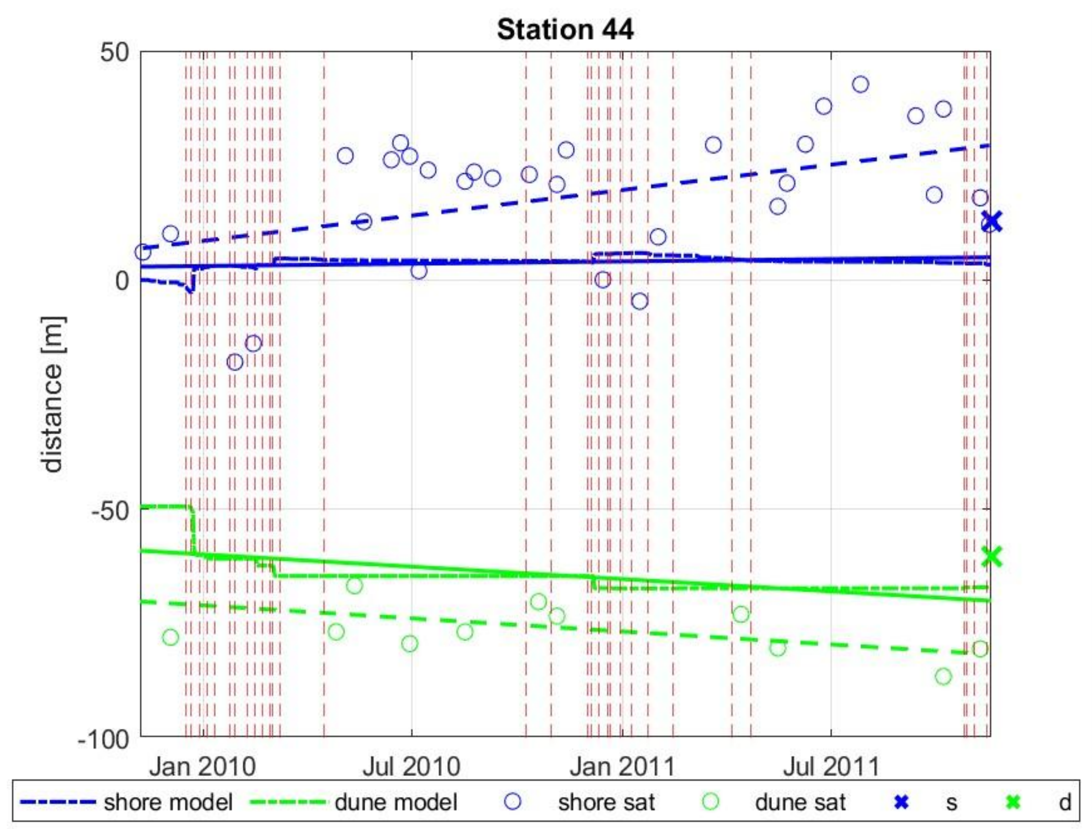

Figure 5. Station 44 time series of modeled shoreline and dune toe changes, overlayed with satellite-derived shoreline positions and NDVI-based dune vegetation lines, used for validation

A wave-shore-dune model was developed to capture the alongshore variability induced by longshore gradients and cross-shore fluxes by dunes interactions. ERA5 waves (corrected using Faro buoy) was propagated using SnapWave to capture large scale refraction induced by the dominant wave direction from SW. Thirty-one storms were identified between the simulation period. For each storms, parameters were extracted. The shore-dune model was validated against satellite derived shore and dune positions for all of the 85 stations.

RESULTS

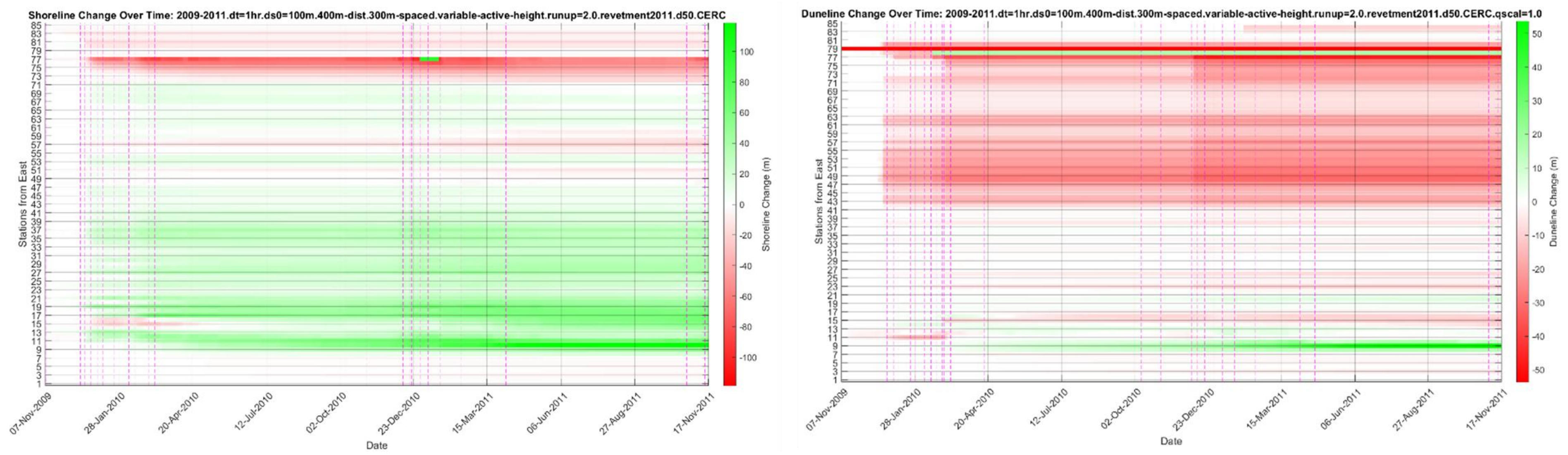

Figure 6: Simulated time evolution of shoreline and dune foot positions along Culatra Island. Westward erosion, eastward accretion, and an erosion hotspot between T42–T77 are captured.

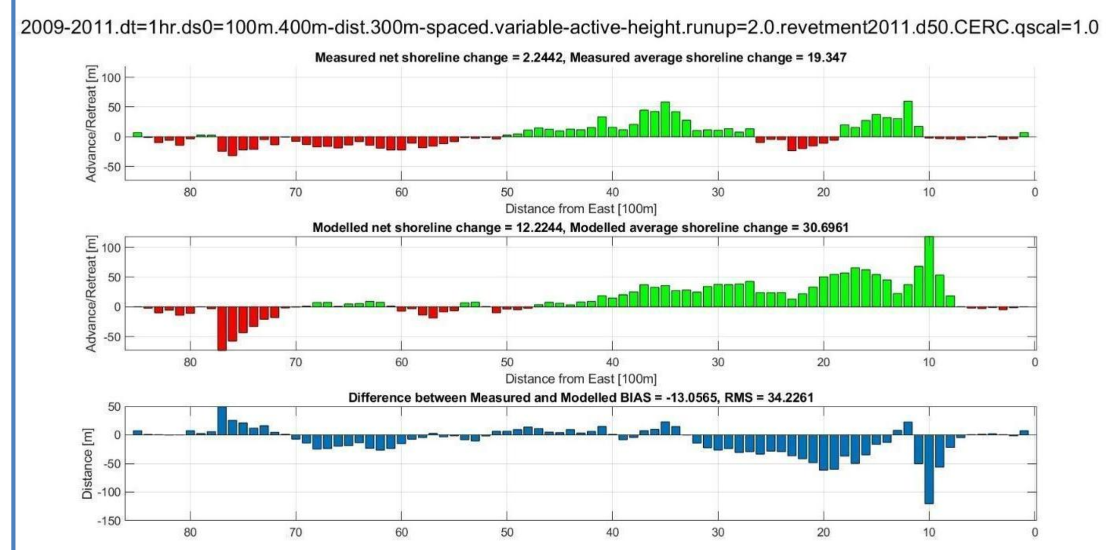

Figure 7. Modeled shoreline change showing overestimation of accretion in the east and erosion in the west compared to observations.

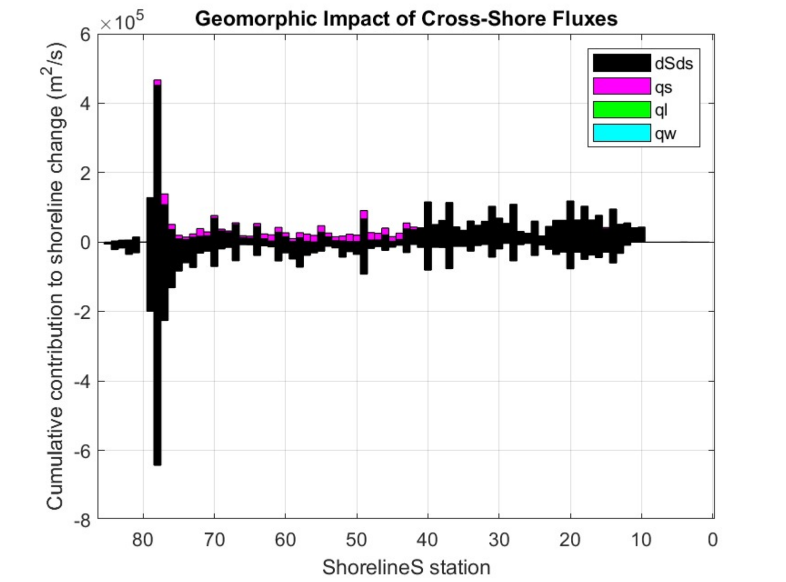

Figure 8. cross-shore sediment fluxes revealing erosion hotspots alongshore, particularly between T42–T77.

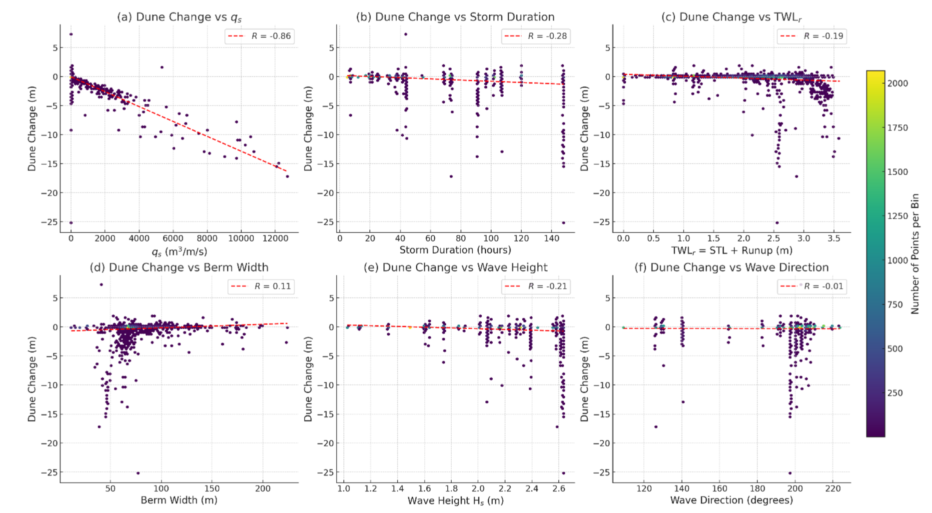

Figure 9. Correlation of dune retreat against storm parameters, with cumulative sediment transport and storm duration, highlighting key storm drivers.

Cumulative cross-shore sediment transport and storm duration emerged as the primary drivers of dune toe retreat, exceeding the influence of peak storm intensity. Dune erosion model results showed good agreement with NDVI-derived vegetation line shifts ($R^2 \approx 0.59$), validating the model's ability to capture alongshore variability in dune response. The clustering of storm events caused compounding effects, emphasizing the importance of integrating cross-shore and alongshore sediment dynamics in barrier island evolution models. Local dune erosion contributed sediment to the adjacent beaches, temporarily buffering shoreline retreat during major storms, particularly in the erosion hotspot between T42–T77.

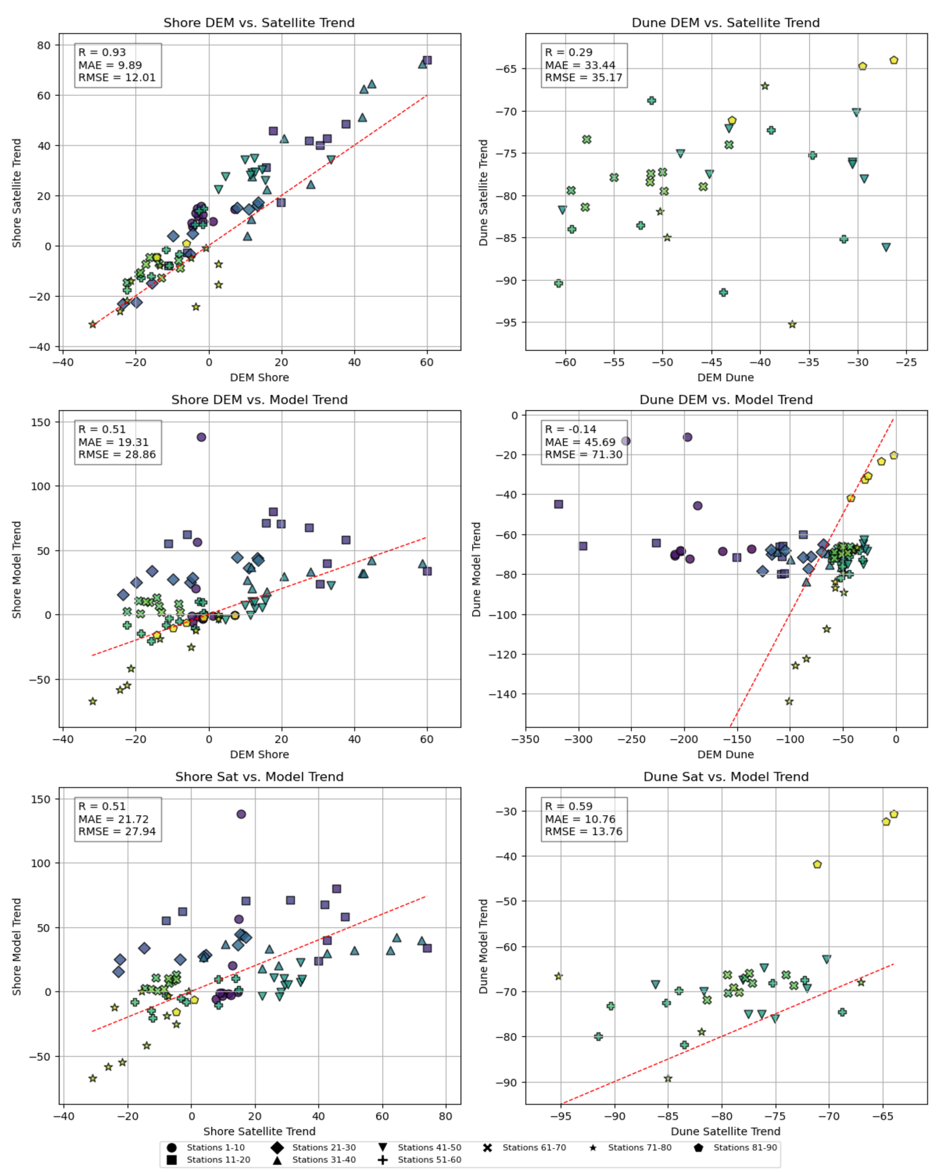

Figure 10 . Validation of modeled shoreline and dune toe positions against satellite-derived shoreline and NDVI-based vegetation lines.