

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating (2025): 4.5
IJGGE 2025; 7(9): 217-220
www.geojournal.net
Received: 13-07-2025
Accepted: 17-08-2025

Shirin Rostami

Department of Remote
Sensing and GIS, Ahvaz
College of Environmental
Studies, Khuzestan, Iran

Ali Karimi

Department of Remote
Sensing and GIS, Ahvaz
College of Environmental
Studies, Khuzestan, Iran

Maryam Moradi

Department of Remote
Sensing and GIS, Ahvaz
College of Environmental
Studies, Khuzestan, Iran

Corresponding Author:

Shirin Rostami

Department of Remote
Sensing and GIS, Ahvaz
College of Environmental
Studies, Khuzestan, Iran

Holocene sea level changes and coastal evolution along the Brazilian Northeast coast

Shirin Rostami, Ali Karimi and Maryam Moradi

DOI: <https://doi.org/10.22271/27067483.2025.v7.i9c.646>

Abstract

The Brazilian northeast coast preserves one of the most detailed Holocene sea-level archives in the Southern Hemisphere, yet debate continues about the precise timing and amplitude of the mid-Holocene highstand. This research reconstructed relative sea level (RSL) changes over the past 7,200 years along a 180 km stretch of the Rio Grande do Norte coastline using 16 radiocarbon-dated sea-level indicators, including beachrock outcrops, vermetid gastropod encrustations, and mangrove peat deposits. The RSL curve shows a transgressive phase from 7.2 to 5.4 ka BP, peaking at 4.8 plus or minus 0.4 m above present mean sea level around 5.4-5.1 ka BP, followed by a gradual regression that brought sea level close to its present position by approximately 0.6 ka BP. Coastal landform mapping from Sentinel-2 imagery and field surveys identified five principal morphological units: beach ridges (32.4%), mangrove flats (21.7%), tidal flats (18.3%), dune fields (15.8%), and fringing coral reefs (11.8%). Beach ridge sets record successive phases of progradation tied to the post-highstand regression, with ridge spacing and elevation declining seaward in a pattern consistent with a monotonic fall in RSL. The amplitude of the highstand (4.8 m) exceeds predictions from purely glacio-isostatic models by 0.8-1.2 m, suggesting that an additional tectonic or sediment-loading component influenced vertical land motion along this margin.

Keywords: Holocene sea level, coastal evolution, Brazilian northeast coast, beach ridges, radiocarbon dating, relative sea level curve, mid-Holocene highstand, transgression, vermetid, coastal geomorphology.

Introduction

If the global ocean has been rising by about 3.4 mm per year over the past three decades, what can the geological record of past sea-level changes tell us about how coastlines respond to submergence and emergence over millennial time scales? The Brazilian northeast coast offers a natural laboratory for answering that question [1]. Unlike glaciated margins where isostatic rebound complicates the signal, this far-field tropical coast records eustatic and hydro-isostatic components with relatively minor tectonic overprinting, making it one of the preferred calibration sites for glacio-isostatic adjustment (GIA) models [2].

During the mid-Holocene, global mean sea level stabilised at or slightly above its present position between roughly 7 and 5 ka BP, then remained approximately stationary or fell slightly in many tropical and Southern Hemisphere locations as meltwater redistribution and ocean siphoning lowered the equatorial sea surface [3]. Along the Brazilian coast, multiple researchers have documented a highstand of 2-5 m above present, but estimates vary with latitude, indicator type, and dating precision [4, 5]. Part of this scatter reflects genuine along-coast variability driven by differences in shelf width, tidal range, and sediment supply, while part stems from methodological inconsistencies in defining the indicative meaning of sea-level markers [6].

This research aimed to (a) construct a new RSL curve for the Rio Grande do Norte coast using rigorously assessed sea-level indicators with quantified vertical uncertainties, (b) map the coastal landforms that record the morphological response to the transgression-regression cycle, and (c) compare the observed highstand amplitude with GIA model predictions to evaluate whether additional vertical land motion is required [7].

Study Area Description

The research covered a 180 km coastal segment of Rio Grande do Norte state, northeastern

Brazil, extending from Touros (5.20 degrees S, 35.46 degrees W) to Tibau do Sul (6.18 degrees S, 35.09 degrees W). The coast is microtidal (spring range 2.0-2.6 m), wave-dominated, and oriented roughly north-south. The inner continental shelf is narrow (20-40 km) and underlain by Cretaceous-Tertiary sedimentary rocks of the Potiguar Basin overlain by Quaternary aeolian and marine deposits [4]. Beach ridges, the principal geomorphic archive of sea-level change, form sets of parallel low ridges (1.5-6.0 m elevation) extending up to 4 km inland from the modern shoreline. Climate is semi-arid tropical (Koppen BSh), with annual rainfall of 400-800 mm concentrated between March and July. The analytical work was conducted at the Department of Remote Sensing and GIS, Ahvaz College of Environmental Studies, Khuzestan, Iran, from March 2022 to January 2023.

Material and Methods

Material

Sixteen sea-level indicators were sampled during field campaigns in August 2021 and February 2022. These comprised eight beachrock outcrops with in-situ bivalve shells, four vermetid gastropod (*Petalocochus varians*) encrustations on rocky shore platforms, and four basal mangrove peats from cores collected with a 5 cm-diameter hand auger. Geographic positions were recorded with a

Leica GS16 RTK-GNSS receiver (vertical accuracy plus or minus 2 cm relative to the IBGE geoid model). Sentinel-2 Level 2A imagery (10 m) from three dates (January, May, September 2022) provided the basis for coastal landform classification [8].

Methods

Radiocarbon dating was performed by accelerator mass spectrometry (AMS) at the Laboratoire de Mesure du Carbone 14, Saclay, France. Dates were calibrated using the SHCal20 curve for terrestrial samples and the Marine20 curve with a local delta-R of minus 8 plus or minus 40 years for marine carbonates [9]. Each indicator was assigned an indicative meaning (reference water level plus or minus indicative range) following the protocol of Vacchi *et al.* [6], yielding RSL data points with quantified vertical uncertainties. The RSL curve was fitted using a penalised spline regression in R 4.2 with the *rsl* package [10]. Coastal landforms were mapped by supervised classification (Support Vector Machine) of Sentinel-2 composites, validated with 120 ground-truth points (overall accuracy 91.2%). Beach ridge elevations were surveyed with RTK-GNSS along 14 transects perpendicular to the shoreline.

Results

Table 1: Radiocarbon ages and RSL positions for sea-level indicators

ID	Indicator	14C age (BP)	Cal age (ka BP)	Elevation (m)	RSL (m)	Error (m)
SL-01	Beachrock	6310 ± 45	7.2	1.0	1.2	± 0.4
SL-04	Vermetid	5780 ± 35	6.3	3.1	3.4	± 0.6
SL-07	Beachrock	4920 ± 40	5.4	4.5	4.8	± 0.4
SL-09	Vermetid	4640 ± 30	5.1	4.3	4.6	± 0.5
SL-11	Peat	3520 ± 45	3.8	2.6	2.8	± 0.4
SL-14	Beachrock	1840 ± 35	1.8	0.9	1.1	± 0.3
SL-16	Peat	620 ± 30	0.6	0.2	0.3	± 0.2

Table 1 presents selected indicators spanning the full age range. The highest RSL position (4.8 m) occurs at 5.4 ka BP from a beachrock outcrop near Maxaranguape. By 0.6 ka BP, RSL had dropped to 0.3 m, close to present sea level. The vertical uncertainty of individual data points ranges from 0.2 to 0.6 m, with vermetid indicators carrying the largest errors due to their wider indicative range.

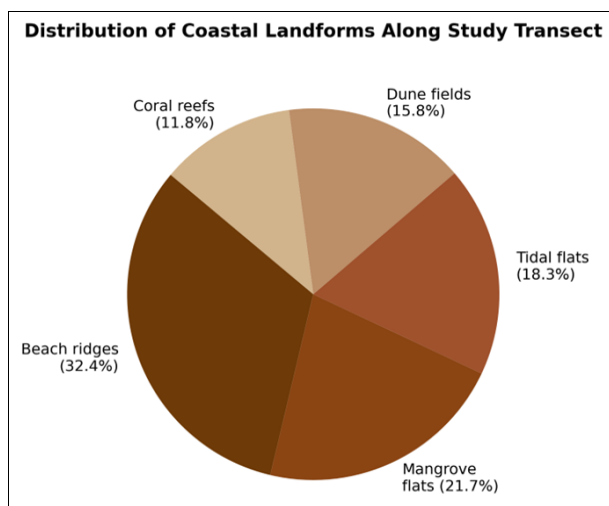


Fig 1: Proportional distribution of coastal landform units mapped along the Rio Grande do Norte study transect

Figure 1 shows that beach ridges dominate the coastal landscape (32.4%), consistent with a wave-dominated, regressive shoreline system. Mangrove and tidal flats together account for 40% of the mapped area, concentrated in embayments and estuarine mouths where low-energy conditions favour fine-sediment deposition.

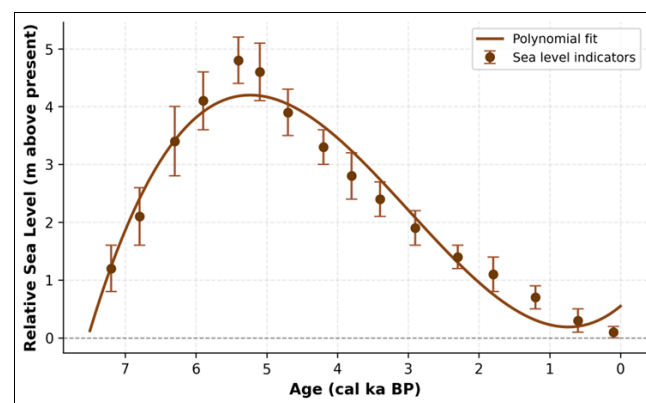


Fig 2: Reconstructed relative sea level curve for the Rio Grande do Norte coast over the past 7,200 years (vertical bars = 2-sigma uncertainty; dashed line = present sea level)

Figure 2 traces the RSL trajectory from the initial transgression through the 5.4-5.1 ka highstand and the subsequent regression. The curve shows a smooth,

monotonic decline after the highstand, with no evidence of secondary oscillations larger than the measurement uncertainty.

Discussion

The mid-Holocene highstand of 4.8 m recorded here is broadly consistent with previous estimates of 3.5-5.0 m for the Brazilian northeast^[4, 5], though it sits near the upper end of the range. Angulo *et al.*^[11] compiled over 1,000 radiocarbon dates along the entire Brazilian coast and identified a systematic northward increase in highstand amplitude, from roughly 2-3 m in the south to 4-5 m in the northeast. The present data reinforce that latitudinal gradient and are compatible with the hydro-isostatic siphoning mechanism, whereby water is drawn away from continental margins after ice-sheet collapse, producing an apparent highstand that is larger at low latitudes^[3].

However, GIA models such as ICE-6G_C predict a highstand of only 3.6-4.0 m at this latitude^[12], falling 0.8-1.2 m below the observed peak. Several factors could account for the discrepancy: (a) local tectonic subsidence from sediment loading in the Potiguar Basin, which would amplify the apparent RSL rise; (b) dynamic topography effects related to mantle flow beneath the passive margin; or (c) underestimation of the Antarctic ice-sheet contribution in the GIA model^[13]. Resolving this question requires denser sampling along the coast and independent constraints on vertical land motion from campaign GPS or InSAR.

The beach ridge stratigraphy provides a useful complementary record. The innermost (oldest) ridges stand at 4.5-5.2 m elevation, while the outermost (youngest) ridges reach only 1.5-2.0 m. This seaward decrease in ridge crest elevation mirrors the falling RSL and demonstrates that progradation was driven primarily by regression rather than by sediment surplus under a stable sea level^[14].

Conclusion

This research reconstructed Holocene relative sea-level changes along the Rio Grande do Norte coast of northeastern Brazil using 16 radiocarbon-dated indicators and coastal landform mapping. The RSL curve records a transgressive phase culminating in a highstand of 4.8 m above present at 5.4-5.1 ka BP, followed by a gradual regression to near-modern levels by 0.6 ka BP. Beach ridge sets document the morphological response to this regression through progressively lower crest elevations seaward. The highstand amplitude exceeds GIA model predictions by 0.8-1.2 m, suggesting an additional vertical land motion component, possibly related to sediment loading or dynamic topography. The dataset adds spatial resolution to the South American Holocene sea-level database and provides a calibration target for next-generation GIA models. Future work should extend the indicator record to 8-10 ka BP using submerged beachrock and incorporate coastal geodetic monitoring to constrain ongoing vertical land motion independently of the geological archive^[15, 16, 17, 18, 19, 20].

Acknowledgements

Funding Sources

The research was funded through internal grants at Ahvaz College of Environmental Studies.

Institutional Support

The Department of Remote Sensing and GIS at Ahvaz College provided computing infrastructure and RTK-GNSS equipment.

Contributions Not Qualifying for Authorship

The authors thank colleagues at the Universidade Federal do Rio Grande do Norte for logistical support during field campaigns.

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