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RESEARCH ARTICLE

Imagery analyses and sediment cores reveal coastal evolution in Cayo Jutías, Northwestern Cuba

Análisis de imágenes y núcleos de sedimento revelan la evolución costera en Cayo Jutías, noroeste de Cuba

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Abstract

Shorelines are being eroded at an accelerated rate in certain sectors of the Cuban Archipelago due to natural and anthropogenic processes. Cayo Jutías, in the northwestern coast of Cuba, has undergone transformation in the last decades including a shoreline retreat of around 10 m y^{-1} and subsequent flooding of the coastal infrastructure. The causes of this accelerated modification are unclear but two drivers seem to be important: the modification of the natural dynamics because of the construction of a land bridge, and a high exposure to meteorological events. Therefore, we aimed to describe the recent coastal evolution of Cayo Jutías based on the coupling of aerial and satellite imagery and sediment records from cores. We used two aerial photographs and three satellite images derived from Google Earth to verify the changes that have occurred in the study area in the period 1970-2017. Three cores were collected in November 2016 to analyze the sedimentary records of texture and composition. Hurricane and storms are the main natural processes affecting the coastal evolution of shoreline in Cayo Jutías, likely in conjunction with sea level rise. Human intervention, mainly the building of the land bridge, likely exacerbated the shoreline changes. The island behaved as a drift sector, with erosion on the northeast end, sediment transport westwards along shoreline, and accumulation on the southwestern end.

Keywords: satellite images, sediments cores, sediments dynamic, coastal evolution, Cuba.

Resumen

Las costas están siendo erosionadas a un ritmo acelerado en algunos sectores del archipiélago cubano debido a procesos tanto naturales como antrópicos. Cayo Jutías, ubicado en la costa noroccidental de Cuba ha experimentado transformaciones drásticas en las últimas décadas, incluyendo retrocesos de la línea de costa de hasta 10 m y^{-1} y una consecuente inundación de infraestructuras costeras. Las causas de esta acelerada modificación permanecen inciertas aun, pero dos indicadores parecen ser importantes: los cambios en la dinámica natural provocada por la construcción de un pedraplén, y la alta exposición a eventos meteorológicos extremos. Por tanto, el objetivo de la investigación es describir la evolución costera reciente de Cayo Jutías basada en el uso de imágenes aéreas y satelitales y en núcleos de sedimento. Dos fotografías aéreas y tres imágenes satelitales obtenidas de Google Earth fueron utilizadas para verificar los cambios ocurridos en el área de estudio entre 1970 y 2017. Tres núcleos de sedimento fueron colectados en noviembre de 2016 con el fin de analizar el registro sedimentario en términos de textura y composición. La incidencia de huracanes y tormentas tropicales parecen ser el principal factor natural modificando la evolución de la línea costera en Cayo Jutías, presuntamente en conjunción con el ascenso del nivel del mar. La intervención humana, principalmente la construcción del pedraplén, puede haber exacerbado los cambios en la línea costera. La isla se comporta como un sector de deriva con erosión en el extremo noreste, transporte de sedimentos hacia el oeste a lo largo de la línea costera y acumulación en el extremo suroeste.

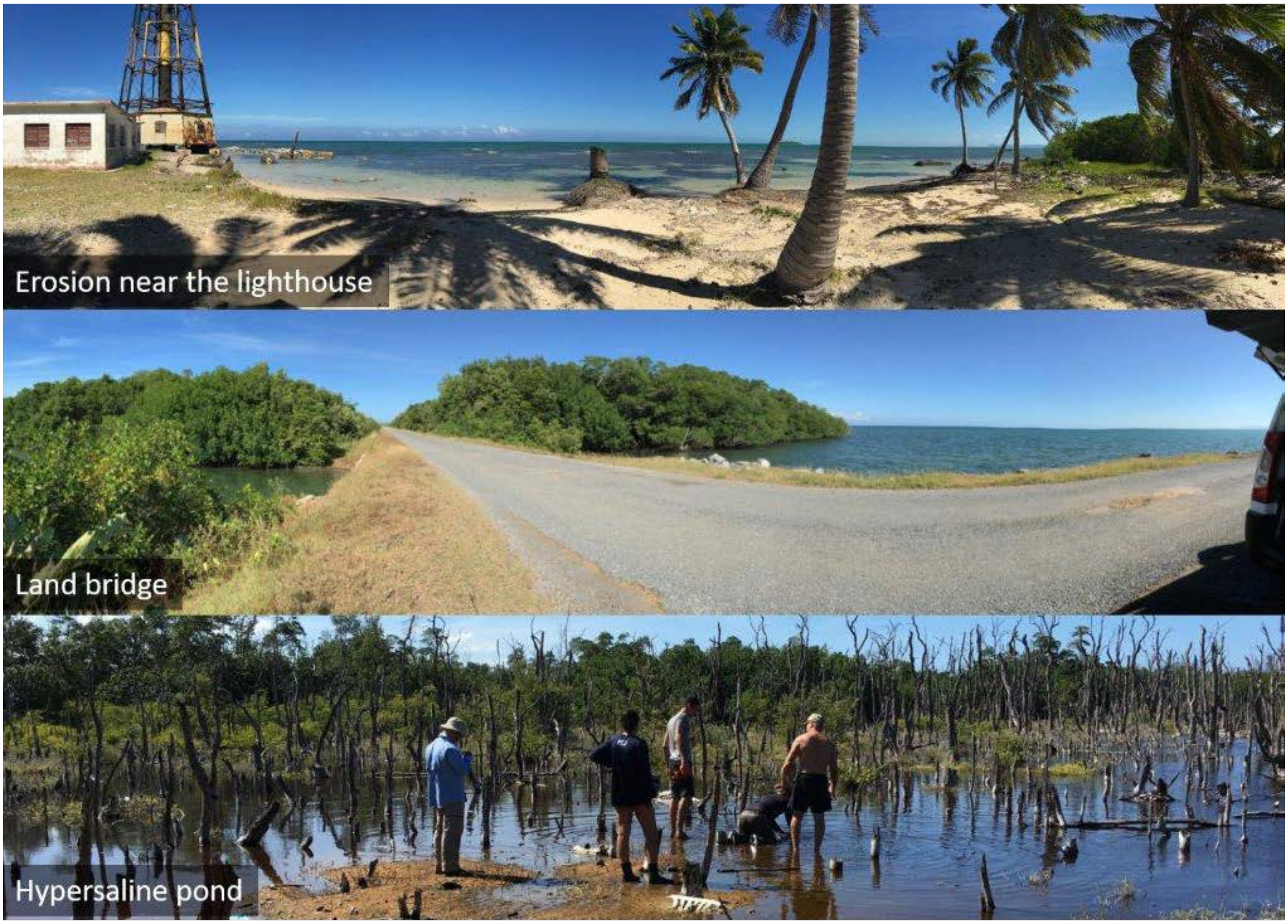
PALABRAS CLAVE: imágenes satelitales, núcleos de sedimento, dinámica de sedimentos, evolución costera, Cuba.

Introduction

The coastal zone, particularly the shoreline, is a heterogeneous region with high variability at several temporal scales. Understanding that variability can help us interpret and forecast how the coasts could change and evolve in a scenario of global change. In addition, sea-level rise, accelerated urbanization of the coastal zone and the damming of rivers have modified patterns of coastal dynamics (IPCC, 2014). Currently, the combination of natural and anthropogenic processes is influencing the configuration of the shorelines and their evolution over time. Islands and barrier islands are fragile and dynamic coastal features and are also vulnerable from both natural and anthropogenic processes (Hapke et al., 2013). The spatial-temporal evolution of shoreline change can be used as a proxy to monitor the coastal environmental change, as the assessment of long-term trends in shoreline change are essential to improve the understanding regarding coastal responses to a changing climate scenario (Xu, 2018). Moreover, this information on coastal changes could help in taking appropriate measures for coastal resilience and sustainability (Sajjad et al., 2018).

Methodologies used to study morphological changes in the coastal zone include remote sensing (e.g., aerial and satellite images) and the sedimentary record (sediment cores). Remote sensing techniques have proved its utility for detecting changes in the coastal zone (Walker et al., 1996; Adegoke et al., 2010; Zhang & Hu, 2016; Kanwal et al., 2020). The large advantage of these methods are the extensive spatial coverage and the diverse types of information generated (e.g., depth, vegetation, water vapor). Sediment records are very effective for understanding the temporal evolution of coastal systems in particular when several proxies are simultaneously analyzed (e.g., grain size, organic matter, fossil record, and dating) (Sainz de Murieta, 2011; Culver et al., 2015; Brooks et al., 2015; Diaz-Asencio et al., 2020). The knowledge of coastal dynamics and its drivers demand an interdisciplinary effort (Dias et al., 2013) indicating that the coupling of both remote sensing and sedimentary record allows for a more extensive, detailed and, reliable reconstruction of the coastal zone evolution and the processes influencing shoreline change.

In the Cuban archipelago, coastal erosion is occurring at an accelerated rate in certain areas (Hernández et al., 2013). These authors reported that the Cuban island shoreline is undergoing significant modifications mostly due to alteration of marine sediment distribution patterns, which is reflected by changes in erosion-accumulation of sediments along the shoreline. Cayo Jutías is



Suplementary figure S1.

a conspicuous sandy island in the northwestern coast of Cuba island characterized by a long shoreline, outstanding beaches subjected to moderate touristic use and a lighthouse with importance for regional navigation (Supplementary figure S1). Cayo Jutías has undergone transformations in the last decades inclu ding a shoreline retreat of around 10 m y^{-1} and subsequent flooding of the coastal infrastructure (e.g., the lighthouse) (Centella et al., 2015). The causes of this accelerated shoreline retreat are unclear but two drivers seem to be important: (i) the modification of the natural dynamics associated with the construction of the lighthouse and a land bridge between the main island and Cayo Jutías; and (ii) a high exposure of the island to higher energy meteorological events such as cold fronts and hurricanes. Other influences include progressive sea-level rise and the loss of physical protection by the degradation of coral reef crests and mangroves.

In this study, we combine aerial and satellite imagery with sediment records from cores to investigate: (1) How Cayo Jutías has responded to anthropogenic and natural processes (high energy events such as tropical cyclones, low systems, cold fronts) that have led to changes in the shoreline configuration; and (2) Identify and characterize the portions of the island that have remained stable over the past decades and those that have experienced active erosion or accretion. The second objective will inform as well about the processes contributing to shoreline stability/evolution to better predict future changes in shoreline configuration. These objectives are very relevant since climate change is one of the five main environmental problems in Cuba due to the high vulnerability of the country as an archipelago to sea level rise (Centella et al., 2015).

Study Area

Cayo Jutías is located at 22° 43' N and 84° 02' W in the northwestern coast of Cuba island (Fig. 1, top panel). The island has a shape of "spit", an approximate area of 4 km^2 and a low elevation of about 2 m above mean sea level. The island is covered by mangrove forest, except on its seaward (north) coast, where there is a long beach of white sand, interrupted by small segments of mangrove patches. Offshore (~1 km) there is a submerged coral reef crest. The island was artificially connected to the mainland by a land bridge built at the beginning of the 1990s (Comisión Nacional de Nombres Geográficos, 2000).

Cayo Jutías sediments are composed of carbonate deposits (mostly to the north), terrigenous and peat (to the south) formed since the Holocene. It is a zone of deposition in the coastal plain with modern vegetation cover (mostly mangrove forest) subjected to recent exogenous processes (Cabrera, 2009).

Materials and methods

Satellite images and aerial photographs

We used two aerial photographs obtained from local flights (1970 and 1997, in digital format) and three satellite images derived from Google Earth (2004, 2010, and 2017) (Supplementary figure S2) to verify the changes that have occurred in the study area. All the images were georeferenced and the position of the old shorelines were digitized (vectorized) by visual interpretation (Hapke et al., 2010). The areas of sediment erosion, accretion and their rates were calculated after digitizing all the images and photographs using the features of the QGIS 2.18 software. The areas of sediment erosion and accretion were calculated after identifying intersections in polygons derived from 1970 shoreline and 2017 shoreline. The rates of erosion/accumulation in different sectors were calculated based on linear distance (meters) between 1970 shoreline and 2017 shoreline divided by the number of years (47). Therefore, the period to be studied through remote sensing is restricted from 1970 to 2017.

To achieve a successful georeferencing, it is essential that each pixel of an "A" image corresponds exactly from the geographical point of view with the pixel of the "B" image (Núñez et al., 2018). We used the 2017 image as base for georeferencing since image coordinates were established by support points. The transformation type was Thin Plate Spline using the Closest neighbor method and was made from the 2017 image canvas. A total of five support points were selected (Fig. 1, bottom panels). The pixel residuals obtained were low warranting minimum displacement errors (Zhou et al., 2011).

Sedimentological and stratigraphic analyses of sediment cores

Sediment cores were collected at three sites in November 2016 using a hand-held corer with two cores per site for stratigraphic and sedimentological analyses to determine changes in sedimentation patterns and environment over time (Fig. 2 and Supplementary figure S1) (Table 1). Core CJ-01 was collected in the western part of the island, in a coastal lagoon open to the sea where the predominant submerged vegetation was *Thalassia testudinum* and the adjacent coast vegetation was *Rhizophora mangle* and *Avicennia germinans*. Core CJ-03 was in the eastern part

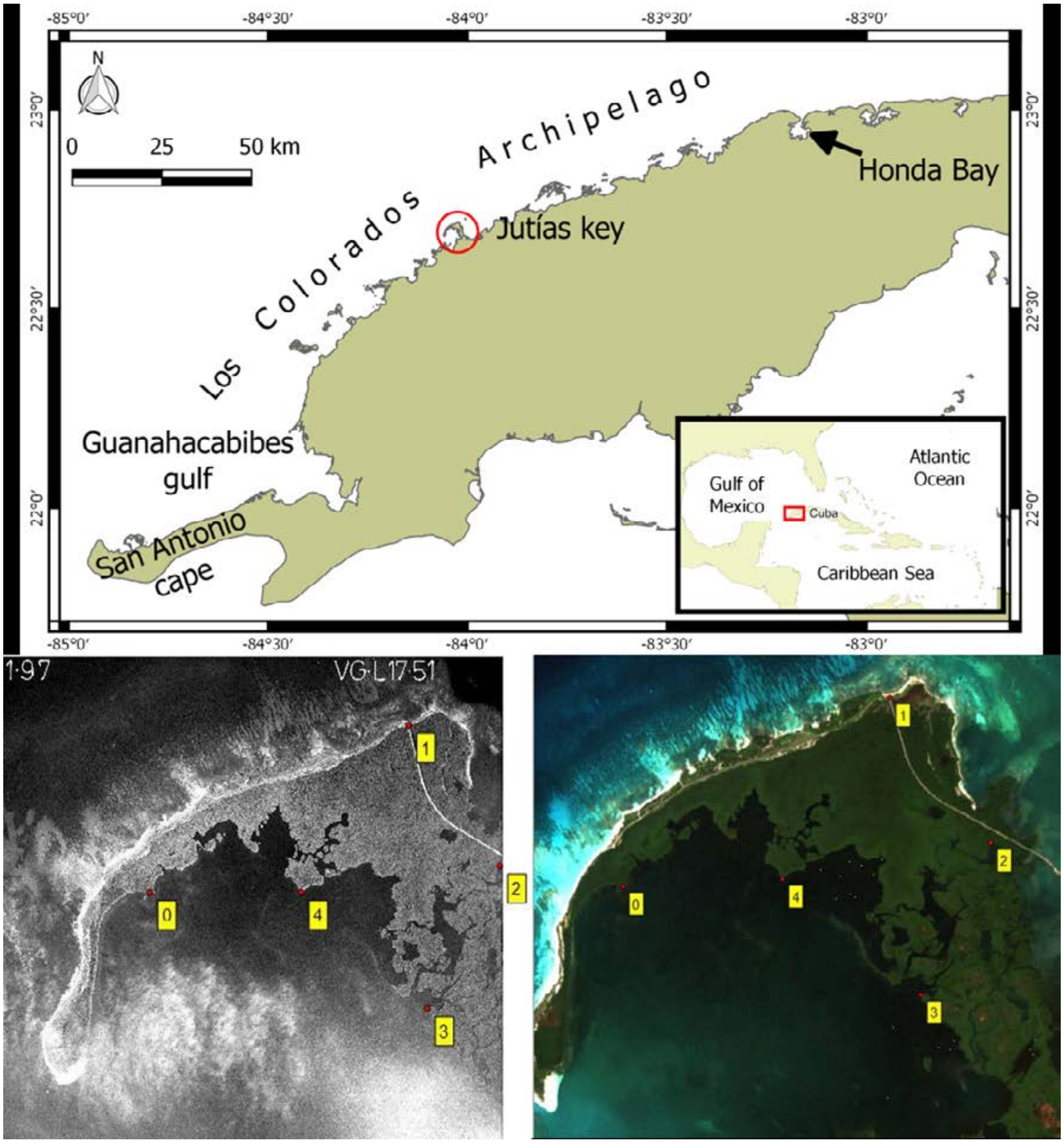


Fig. 1. The sampling site. Top: Cayo Jutías, in the northwestern region of Cuban archipelago. Bottom: 1997 (left) and 2007 (right) images with five georeferenced points indicated.

of the island, in a coastal lagoon with a protective dune of approximately 1.5 m elevation above sea level. The predominant vegetation was *R. mangle* with a certain degree of environmental degradation as indicated by dead trees. Core CJ-05 was taken in the eastern part as well, just south of the lighthouse, in a coastal lagoon that is separated from the marine environment only by a small unvegetated berm. The predominant vegetation was *R. mangle* but most of the trees were dead indicating significant environmental change and degradation.

Sediment compaction in the cores during the collection was negligible warranting a reliable

Table 1. Sampling information about the three cores collected in Cayo Jutías.

Core label	Date of collection	Latitude (N)	Longitude (W)	Core length (cm)	Observations
CJ-01	Nov., 4th, 2016	22°41’48”	84° 03’13”	43	Small inlet within the mangrove forest, open to the sea
CJ-03	Nov., 4th, 2016	22°42’48”	84° 01’14”	64	Small salty pond with protection of dune and visible erosion
CJ-05	Nov., 4th, 2016	22° 42’52”	84°01’18”	70	Large salty pond with visible over washing on berm. Many dead trees in the lagoon

integrity of the sedimentary facies (García-Artola et al., 2011). One sediment core per site was split longitudinally, photographed and described. The second core was vertically extruded and sectioned at 0.5 cm intervals according to the methodology of Schwing et al. (2016); samples were analyzed for sediment texture and composition. Sediment texture (i.e., grain size) was determined for content of sand (% Sand), silt (% Silt), and clay (% Clay) by initially wet sieving the sample through a 63 µm sieve. The sand-size fraction (i.e., > 63 µm) was weighted and the fine-size (< 63 µm) fraction was measured

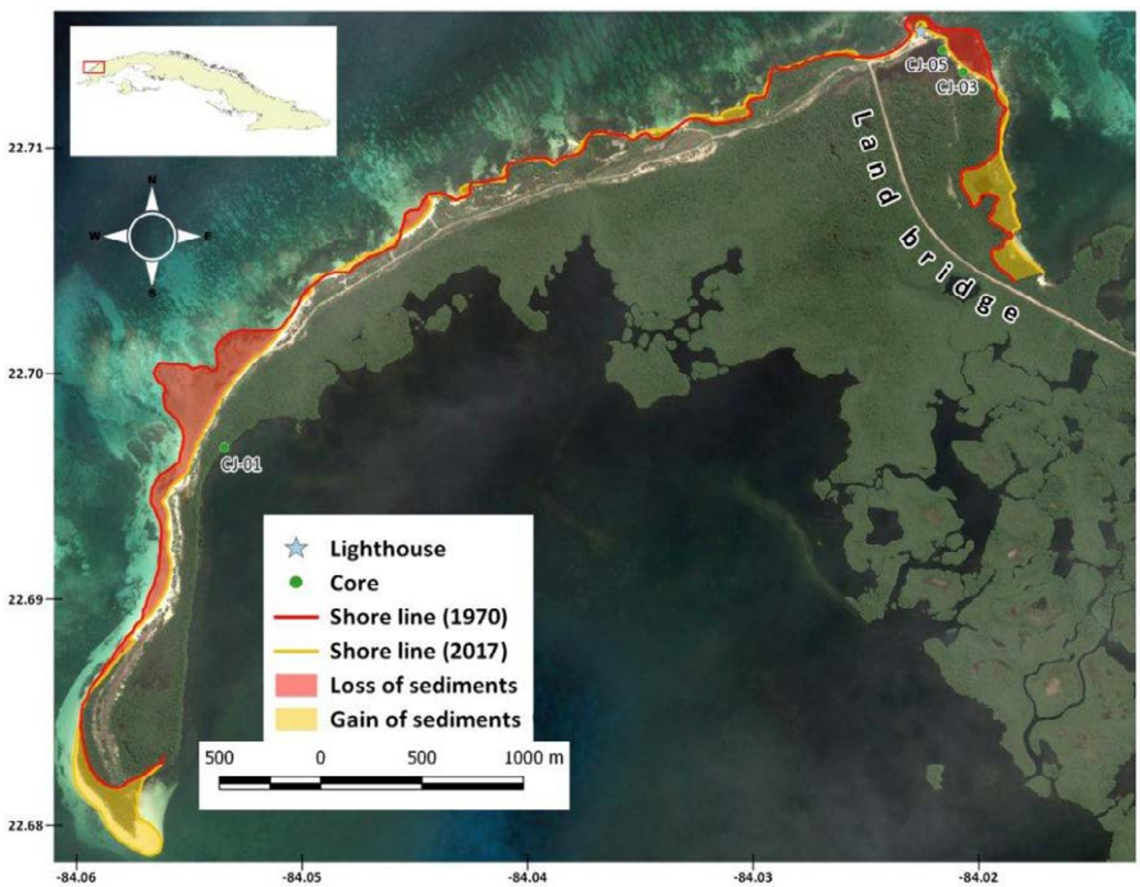


Fig. 2. Sediment dynamics in Cayo Jutías between 1970 and 2017. Red and yellow areas indicate erosion and accretion areas respectively. Green points indicate the location of the sediment cores (CJ-01, CJ-03, and CJ-05).

by the pipette method (Folk, 1965) to determine % Silt and % Clay.

Composition analyses included measures of carbonate content (%$CaCO_3$) by the acid leaching method according to Milliman (1974); total organic matter content (%TOM) by loss on ignition at 550 °C for at least 2.5 h (Dean, 1974); and terrigenous content (all non-carbonate and inorganic). The %TOM was not determined for core CJ-05 and therefore not presented.

Results

Remote sensing

The comparison of aerial photographs and satellite images showed areas with little to no change and areas with significant change in the configuration of the coastline between 1970 and 2017 (Fig. 2). The area of least change (stable) was the central portion of the island and areas of greatest change (unstable) were located toward the ends of the island (northeast and southwest). The central area of more stable coastline was characterized by sand beaches with little evidence of active erosion or environmental degradation, is inshore of a more robust section of the offshore reef crest and has areas covered with mangrove patches. The total estimated eroded area of the island was ~ 261 × 10^3 m^2 and the estimated area of accumulation (i.e., new land) was ~ 221 × 10^3 m^2 resulting in a net area loss of ~ -40 × 10^3 m^2.

Northwest and southwest sectors

The northwest sector has experienced intense erosion (highlighted in red) with areas having an average retreat of the coastline up to 5 m y^{-1} between 1970 and 2017 (Fig. 2). This sector of erosion is likely linked to the southwest sector of accretion (sediment moving landward) which has led to the extension of the spit. An amount of sediment equivalent to approximately 90 × 10^3 m^2 of surface have been transported and deposited into the southwest sector of the island with no clear pattern of deposition in terms of consistency with land bridge construction or storms activities. This deposition has facilitated the colonization of the area by terrestrial plant species (pers. observation)

Northeast and southeast sectors

The sediments of the northeast sector have likely migrated towards the southeast sector, which has led to the formation of a new coastal lagoon and a new sand bar (highlighted in yellow) at a rate of about 20 m y^{-1} between 1970 and 2017. In the area between the lighthouse and the land bridge, 57 × 10^3 m^2 of mangrove forest was lost and led to the formation of a hypersaline pond, a process that occurred mostly during the period from 1997 to 2004.

The erosion pattern in the northeast sector of the island (near the lighthouse) has remained the same since 1970, but in the period 2004–2010 the satellite images analysis revealed an increase in the overall average of the coastline retreat (Fig. 3) (Table 2).

The 2004–2010 period of accelerated erosion was also reflected in the accretion of sediments in the southeast sector, where the average advance of the sand bar and the overall rhythm of sediment accumulation decreased (Fig. 3). The low composite average accumulation of sediments in the sand bar of the periods

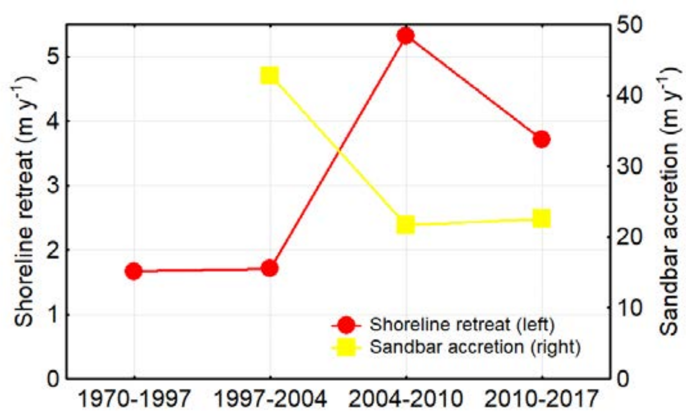


Fig. 3. Accretion (yellow color) and retreat (red color) rates of the shoreline in southeast and northeast sectors of Cayo Jutías calculated from satellite images for different periods. Periods were defined on the basis of image availability and resolution.

Table 2. Shoreline changes in the studied periods. Negative values indicate retraction of shoreline and positive values indicate sand bar accretion. * Period with increment in hurricane activity in the vicinity of the key. ** In this period started the formation of the coastal lagoon and sand bar in the southeast sector.

Variable	Sector	1970-1997	1997-2004	2004-2010*	2010-2017
Total change of shoreline (m)	Northeast	-45	-12	-32	-26
	Southeast	**	300	130	158
% of change	Northeast	39	10	28	23
	Southeast	**	51	22	27
Average rate of change of shoreline (m y^{-1})	Northeast	-1.7	-1.7	-5.3	-3.7
	Southeast	**	43	22	23

2004–2010 and 2010–2017 coincided with the high values of erosion in the same periods in the vicinity of the lighthouse (northeast sector), so that a considerable net loss of sediments can be inferred on the island during this period (Fig. 3) (Table 2).

Sediment cores

The CJ-01 core consisted of dominantly carbonate sands to gravels with two well-defined sedimentary units based upon visual description (Fig. 4). The basal unit extended from the base (43 cm) to approximately 12 cm downcore was light pinkish tan in color and consisted of high carbonate sands to gravels and likely corresponded to a marine-dominated environment. The surficial unit, from 12 cm to the surface, contained also high carbonated sands, but was dark brown with tan (sand) in color. As compared to the downcore marine unit, the surficial unit consisted of lower % Sand (65 % versus 75 %), lower % $CaCO_3$ (85% versus 95 %), and higher % TOM (10% versus 3%). This reflects a transition from a higher energy marine environment to a more restricted marine lower energy and higher biological productivity environment at ~12 cm.

Core CJ-03 consisted of three units with greater variability in the texture and composition as compared to CJ-01 (Fig. 5). The basal unit, from the base (64 cm) upcore to 45 cm was visually similar to the basal unit of CJ-01 with a light pinkish tan carbonate sands and likely reflects a marine environment. A transitional unit from 45 to 20 cm downcore, consisted of dark brown with tan (sands) and was characterized by upcore decrease in %$CaCO_3$ from approximately 75% to 37% (from 25 to 20 cm) and increase in % TOM from ~20% to almost 60% (also from 25 to 20 cm). The surficial unit from 20 to 2 cm depth to surface, had dark color (brown to black) and contained abundant fibrous organic material throughout. It was characterized by low content of % $CaCO_3$ and %Sand (approximately 40% and 7% respectively) and high % TOM (50%) likely reflecting a mangrove environment. In the surficial 2 cm of the core, there was an apparent reversal with an increase of % $CaCO_3$ from 33% to 50%, an increase of %Sand from 0% to 19%, and a decrease of % TOM from 53% to 30%.

The core CJ-05 was the longest core collected and contained a more complex stratigraphic pattern with up to seven stratigraphic units if compared with the previously described units in CJ-01 and CJ-03 (Fig. 6). The basal unit from core base (70 cm) to 66 cm was light pinkish tan carbonate sands similar to the basal units of CJ-01 and CJ-03, likely reflecting a marine environment. From 66 cm to 50 cm sediments were dark

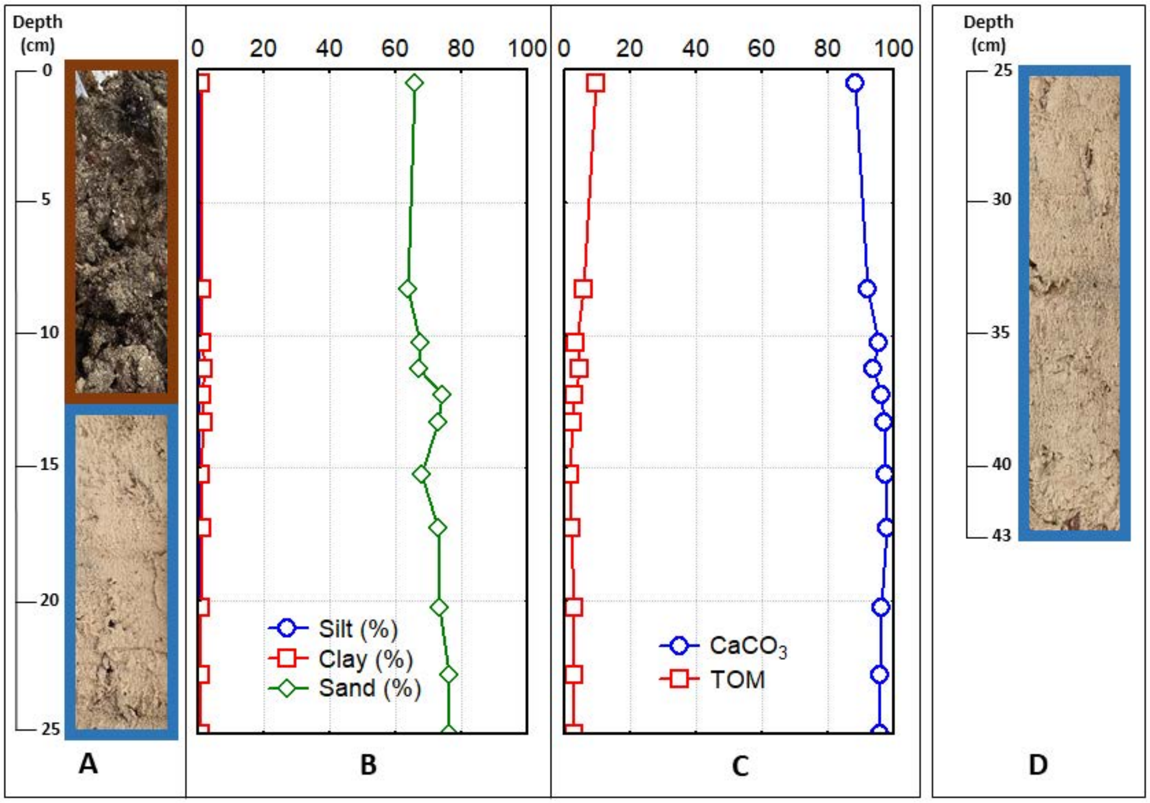


Fig. 4. Sediment core CJ-01 at southwest of Cayo Jutías. (A) Photograph from 0 to 25 cm. (B) Grain size. (C) Carbon composition. (D) Photograph from 25 to 43 cm. Blue frame corresponds to marine dominated environment. Brown frame corresponds to a more restricted marine lower energy environment.

brown to tan sands similar to the transitional unit in CJ-03. The unit from 50 cm to 23 cm consisted of dark (brown to black) and fibrous organic material similar to the surficial unit of CJ-03 likely reflecting a mangrove environment. Sediments return to the transitional unit of dark brown with tan sands from 23 cm to 19 cm before returning to the dark color (brown to black) between 19 and 17 cm. This oscillation in sedimentary units precedes the surficial unit (17 cm to core top) which is drastically different than previous downcore units. This surficial unit is defined by a sharp and large increase of %Sand (from ~ 50% to ~ 100%) concurrent with decreases in the %Silt (from 45% to 0%) and %Clay (from 33% to 0%). Also, the content of %$CaCO_3$ increases in the surficial unit. In the top 2–3 cm of the core, there was a decrease of %Sand (from 90% to 70%) and %$CaCO_3$ (from 97% to 85%), with an increase of mud (%Silt + %Clay) of about 20%.

DISCUSSION

The integration of evidence from remote sensing and sedimentary records indicated a significant modification of the shoreline and coastal environments between 1970 and 2017. The most changes have occurred at the eastern and western ends of the island and those indicate that shoreline change is primarily associated with inlet tidal-dominated process of erosion and landward transport for island migration (Nienhuis & Lorenzo-Trueba, 2019). The central portion remained relatively stable over the studied time period. This central portion may be less vulnerable due to the protection from high-energy events

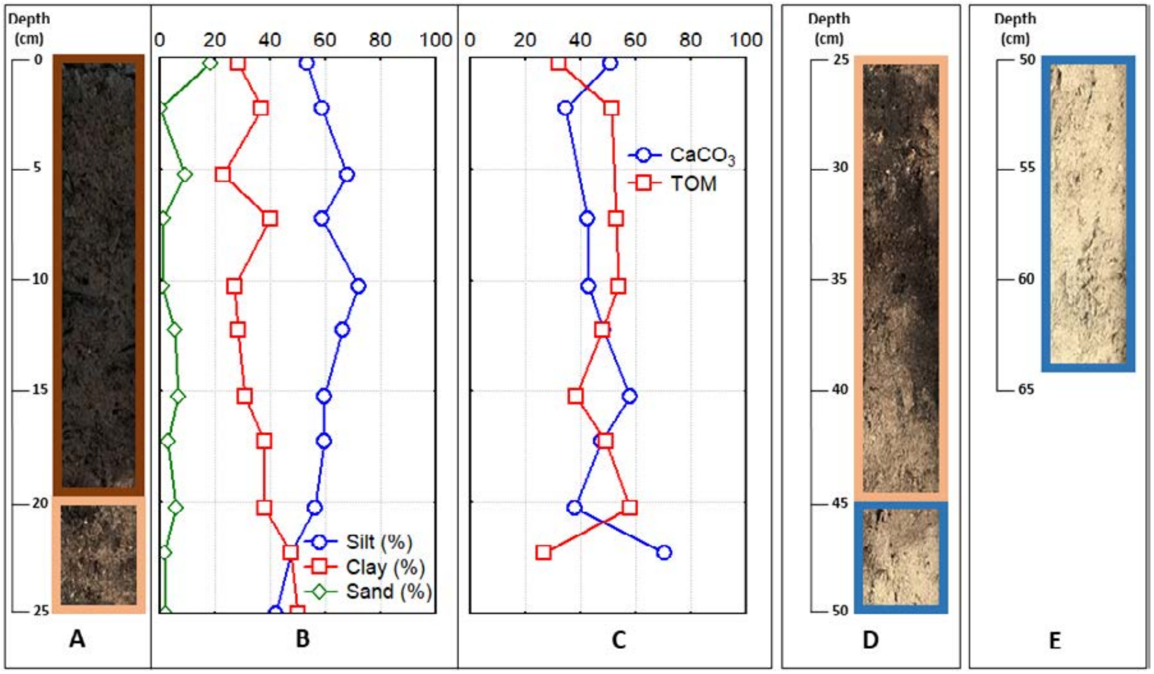


Fig. 5. Sediment core CJ-03 at northeast of Cayo Jutías. (A) Photograph from 0 to 25 cm. (B) Grain size. (C) Carbon composition. (D) Photograph from 25 to 50 cm. (E) Photograph from 50 to 64 cm. Blue frame corresponds to marine dominated environment. Brown frame corresponds to mangrove environment. Peach frame corresponds to a transitional unit.

provided by the offshore reefs and the mangroves patches in the shoreline.

Anthropogenic activities have caused modifications in the coastal evolution as well. The most important stressor has been the construction of a 6.5 km land bridge connecting the main land with the island in order to enhance the communication with the touristic facilities there. This sort of bridge was built by piling a huge number of stones, cemented with asphalt on top. There are only five passages connecting the water bodies at both sides of the road. The width of all the passages summed is about 160 m resulting in less than 3% of the total length of the land bridge interrupting free exchange of seawater across the bridge. The result has been the significant reduction of the water and sediment coastal circulation around the island. A hypersaline pond has formed in the northeast of the island between 1997 and 2004 causing the destruction of an extensive area of mangrove forest (ca. 57×10^3 m^2). In the 1997 aerial picture, the mangrove forest seems to be very healthy and in the 2004 satellite image seems to be in bad conditions. This depletion happened likely to the combination of land bridge construction in early 1990's and storm activity during years 2002 and 2004 since after land bridge construction and 2002 there was no significant storm activity near the island (Supplementary table 3). The increase of sediment erosion in that sector of the island plus sea-level rise has reduced the accretion of the soil acting in synergy against the survival and resilience of the mangrove forests (McIvor et al., 2013).

Sediment records at all sites contained similar stratigraphic sequences suggesting that environmental changes have occurred in the whole island over time, but also reflected sector-specific shoreline changes. The general stratigraphic pattern consisted of a basal unit of

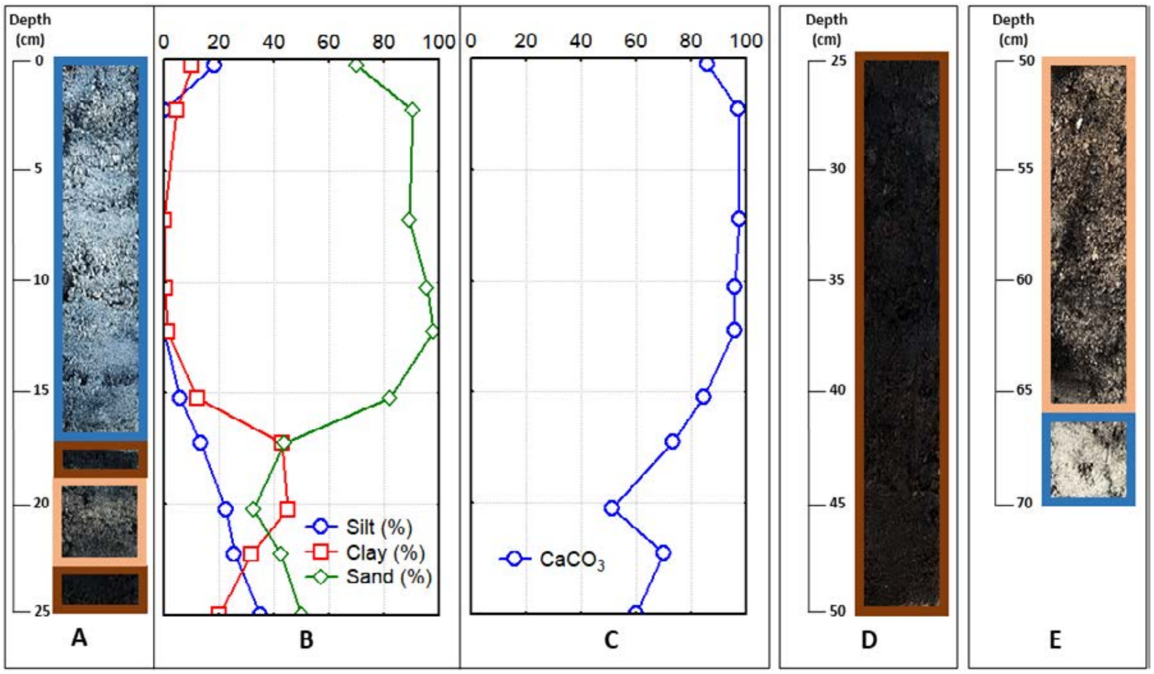


Fig. 6. Sediment core CJ-05 at northeast of Cayo Jutías. (A) Photograph from 0 to 25 cm. (B) Grain size. (C) Carbon composition. (D) Photograph from 25 to 50 cm. (E) Photograph from 50 to 70 cm. Blue frame corresponds to marine dominated environment. Brown frame corresponds to terrigenous environment. Peach frame corresponds to a transitional unit

carbonate sands reflecting a marine/lagoonal environment. All cores indicated a change to a more restricted marine environment (lower energy, possibly seagrass bed) with the dark brown with tan sand unit. Sites CJ-03 and CJ-05 progressed into a stratigraphic unit with high organic content likely representing a mangrove/marsh environment as these areas become a part of the island. CJ-05 was the only site with a surficial unit of higher carbonate sands reflecting the return of a marine influence. Although site CJ-03 may be showing indications of an increase in marine influence at the very surface as well.

The western portion of the island has undergone sediment erosion in the northwest sector, subsequent transport landward and deposition in the growing spit (southwest sector). This process has been occurring over a period of time long enough for vegetation to become established on the spit formation. The change in sedimentation in the surficial unit of core CJ-01 indicated a reduction of physical disturbance in the lagoonal environment in this area likely due to the influence of the landward migration of the spit, but also may be an indication of reduced water flow associated with the construction of the land bridge.

The eastern portion of the island has undergone similar changes with the northeast sector being highly vulnerable to erosion particularly near the hardened structure of the lighthouse. This is also indicated by the surficial marine deposits on top of the core CJ-05, which show an increase in marine sediment deposition associated with high energy events such as cold fronts or storms. This indicates significant overwash occurring with waves transporting marine sands up to 30 m inland. The recent death of mangrove forest in the hypersaline lagoon was evident in the sedimentary record (~2–3 cm depth) and this degradation may further contribute to destabilization of the coastline over this sector. The sediment erosion in the northeast sector appears to be transported landward and has been building out the coastline in the southeast sector over this time period, although there are indications of recent erosion in this area with visible erosive scarps on the shoreline. This evolution is reflected in core CJ-03 with the progression of a marine/lagoonal environment (basal unit) transitioning to a lower energy environment (change in shoreline and bridge construction) and subsequently mangrove marsh became part of the island. The very surficial sediments may be reflecting the recent changes in this area from deposition to erosion. According to the erosive trend of this sector, the evolution of this site would follow the CJ-05 core, with an ending point of a shoreline with dead mangroves, dominated by progressively retreating deposits of marine origin. The location of the old lighthouse, and the construction of a new one very close to the old one, is highly compromised in the scenario of erosion of the northeastern sector and sea-level rise.

The intense and relatively fast coastal dynamics of Cayo Jutías seems to be determined by a combination of natural and anthropogenic processes. Hurricanes and tropical storms, mostly coming from the south, are the most important extreme events affecting Cayo Jutías. The rate of erosion/accretion of sediments intensified during the period 2004-2010 likely because the increase in storm activity near the island. For instance, in 2008 the eyes of three hurricanes (categories 3 or 4) passed within a radius of 50 km around the island (Supplementary table 3).

Conclusions

Hurricanes and storms are the main natural processes affecting the coastal evolution of shoreline in Cayo Jutías. Anthropogenic impacts acting at global- and local-scales (sea level rise and building of land bridge,

Supplementary table 3: Main hurricanes/storms that hit Cuba since 1970. *PR: Pinar del Río (Province were Cayo Jutías is located). **W/L: Wave/Low. Source: Adapted from the original of Meteorological Institute of Cuba, 2016.

No.	Name	year	month	days	SAFFIR SIMPSON Category	Affected provinces															
						*PR	IJ	ART	MYB	LH	MT	CF	VC	SS	CA	CM	LT	GR	HG	SC	GT
1	Allen	1980	August	6-7	1	1	1	0	0	0	0	0	0	0	0			1	0		
2	Kate	1985	November	18-19	2		0	1	2	2	2	1	2	2	2	2	0				
3	Gilbert	1988	September	12-14	1	1	1	0	0	0	0	0	0	0	0	0	0	0		0	
4	Lili	1996	October	17-19	2		2	0	1	0	2	2	1	1	1	0					
5	George	1998	September	23-26	1			0	0	0	1	0	1	1	1	1	1	1	1	1	1
6	Michelle	2001	November	4	4	0	4	0	1	0	4	4	2	1	0	0					
7	Isidore	2002	September	20	1	1	1	0	0	0											
8	Lili	2002	September	29	2	2	2	0	0	0	0	0									
9	Charley	2004	August	12	3	1	1	3	1	3	0										
10	Ivan	2004	September	14	4	4	1	0	0	0											
11	Dennis	2005	July	8-9	4		0	0	2	1	3	4	0	3	3	3	0	4	0	0	0
12	Gustav	2008	August	30	4	4	4	4	0	0	0										
13	Ike	2008	September	7-9	4	1	0	1	0	0	0	0	0	0	0	2	3	0	4	0	0
14	Paloma	2008	November	8-9	3	**W/L										3	2	0			
15	Sandy	2012	October	25	3													1	2	3	1
16	Mathew	2016	October	4	4														?	0	4

respectively) have influenced the coastal evolution as well. As a result, the shoreline of the island behaves as a drift sector and landward retraction have occurred since decades ago.

The central portion of the island has remained stable over the studied period likely due to the protection from high-energy events provided by the offshore reefs and the mangroves in the shoreline. In the northwest sector of the island, no clear links between erosion and anthropogenic activity were identified. On the contrary, in the northeast sector, erosion has been strongly enhanced by construction of a land bridge, which increased vulnerability of the sector and made it less resilient to extreme meteorological events. Sedimentary records indicated that modification of the shoreline has undergone by several decades.

Our results contribute to understand and predict the coastal evolution in Cayo Jutías and other small islands; as well as the synergy between natural processes and development of infrastructure in the coastal zone.

Authors contribution*:*

*"**Conceptualization,*** AMS, RL, GB and MA; ***Methodology,*** AMS, MDA, RL, GB and MA; ***Software,*** AMS and CFD; ***Validation*****,** AMS, RL, GB and MA; ***Formal analysis,*** AMS, CFD, RL, AH, LA and SC***; Investigation,*** AMS, MDA, RL, GB and MA***; Resources,*** GB; ***Data curation,*** AMS, MDA, RL, AH, LA, SC, GB, MA; ***Writing – original draft preparation,*** AMS and CFD; ***Writing – review and editing,*** AMS, RL, GB and MA; ***Visualization,*** AMS, RL, GB and MA***; Supervision,*** AMS, GB and MA***; Project administration,*** GB; ***Funding acquisition,*** GB".

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Conflicto de intereses

Los autores declaran que no existen conflictos de intereses.

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