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Honduran Reef Island Shoreline Change and Planform Evolution over the Last 15 Years: Implications for Reef Island Monitoring and Futures

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Abstract: Assessing the vulnerability of low-lying coral reef islands is a global concern due to predictions that climate and environmental change will increase reef island instability and cause reef island populations to be among the first environmental refugees. Reef islands in the Pacific and Indian Oceans are highly dynamic environments that morphologically adjust to changing environmental conditions over annual-decadal timescales. However, there is a paucity of reef island shoreline change data from the Caribbean where sea-level rise, ecological and environmental disturbance and hydrodynamic regimes are considerably different than in other oceans globally. Here we present shoreline change analysis of 16 reef islands in northern Honduras, at the southern end of the Mesoamerican Barrier Reef. Satellite imagery from a maximum period of 12.4 years from Utila (2006–2019), and 2.4 years from Cayos Cochinos (2018–2021) was analysed to quantify island shoreline change and planform morphological adjustments. We identified accretion as the dominant island behaviour in Utila, where 5 of 7 islands increased in area and 61.7% of shorelines accreted, contributing to an overall net area increase of 9.4%. Island behaviour was more variable in Cayos Cochinos, where 55.7% of shorelines eroded, 5 of 9 islands remained stable, and net island area change was insignificant (2%). Conversely, the 4 smallest Cayos Cochinos islands (all <1500 m^2) experienced significant shoreline change, potentially highlighting a new size threshold for considering reef island evolution. Across both sites, reef islands demonstrated a range of modes of planform change, including lateral accretion and erosion, and migration. Consequently, we provide the first empirical evidence of the dynamic nature of Caribbean reef islands during a period coincident with sea-level rise and highlight the heterogeneous nature of reef island evolution between and within two neighbouring sites at timescales relevant for island adaptation efforts.

Keywords: reef islands; sand cays; shoreline change; planform change; island evolution; resilience; erosion; Mesoamerican Barrier reef; caribbean; sea-level rise

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1. Introduction

Coral reef islands are low-lying accumulations of unconsolidated sediment produced entirely from surrounding coral reefs [1]. They are globally significant environments, providing the only habitable land in reef island nations; socio-economic services for coastal communities, mostly from tourism; and habitats for a range of endemic species [2,3]. However, due to their low elevations and reliance on reefal sediment, reef islands are also considered to be highly vulnerable to environmental change. Global sea-level rise and increasing storm intensity are predicted to increase island inundation, shoreline erosion and salinization; and ongoing coral reef degradation is predicted to reduce island sediment supplies [4–7]. These projections have increased global concern over the long-term stability and habitability of reef islands, so much so that the Marshall Islands and Tuvalu have recently developed the Rising Nations Initiative to preserve the sovereignty and rights of Pacific atoll island nations threatened by sea-level rise [8,9]. However, such perceptions of vulnerability are often built on an incomplete understanding of reef island evolution and their capacity to morphologically adapt to environmental change. This lack of knowledge greatly compromises our ability to predict the future stability and habitability of reef islands globally [10].

To improve the accuracy of reef island vulnerability assessments, and develop appropriate adaptation approaches for island communities, it is important to understand the morphological dynamics of reef island responses to changing boundary conditions across a range of timescales [11]. Over geological timescales, studies have revealed that reef islands form and evolve in response to both rising and falling sea level, [12–17], as well as to ecological and hydrodynamic conditions associated with sea-level changes [18–20]. Over decadal timescales, research has assessed changes to reef island planform areas, and rates and magnitudes of shoreline movements using remote sensing techniques. In the Indian and Pacific Oceans, reef islands appear to be highly geomorphologically dynamic, and able to adjust their shoreline positions during periods of sea-level rise and coral reef degradation [11,21–27]. Indeed, many of these islands have exhibited a range of accretionary behaviours, including expansion towards the ocean or lagoon side of the reef platform, and lateral (spit and extremity) accretion from the central island core [11,28,29]. In many instances, several smaller islands have even agglomerated into larger individual islands [11,25,26]. This research suggests that reef islands globally may not be as vulnerable to future environmental change as once thought, with a recent review concluding that, over the last 50 years, 88.6% of atoll island shorelines had either remained stable or accreted—a stark contrast to predictions of reef islands 'drowning' in response to sea-level rise [11].

Despite this optimism, given the substantial gaps in reef island databases, caution must be applied when trends in atoll island stability, dynamism and future habitability are assumed for reef islands globally. The largest of these gaps, geographically, is from the Caribbean—a region currently experiencing rapid sea-level rise (1.7 ± 1.4 mm/yr during 1993–2010 [30]. Due to spatial differences in eco-environmental factors known to impact reef island formation and evolution, inferences regarding reef island futures from the Indian and Pacific Oceans cannot readily be applied to the Caribbean [11]. Compared to the Indian and Pacific Oceans, the Caribbean has a unique sea level history [31], hydrodynamic regime [32], and coral reef disturbance record [33,34]. More specifically, and most relevant for reef island evolution, extensive coral reef degradation during the 1980s caused great concern over Caribbean reef health, sediment production, and thus Caribbean reef island stability [34–37]. To the best of our knowledge, just two studies have been conducted on Caribbean reef island evolution (locally known as sand cays), which both used traditional map drawing and GPS data to manually map the beach ridge edges of the Sapodilla Cays, Belize [38–40]. These cays show some similarities with those in the Indian and Pacific Oceans, particularly regarding their highly dynamic nature [39]. However, long-term and significant trends of erosion identified on the Sapodilla Cays between 1962 and 2012 contrast the accretionary trends identified for Indian and Pacific reef islands over a similar period [11]. With climate change and associated eco-environmental change predicted to accelerate [41], additional reef island evolution data from the Caribbean is thus required to better resolve the future trajectories of these environments.

Here we present the first, to the best of the authors' knowledge, quantitative assessment of reef island shoreline change and island evolution within the Caribbean using GIS methodologies consistent with those from shoreline change research conducted in the Indian and Pacific Oceans. Specifically, we (1) examine the rates and magnitudes of shoreline change from seven reef islands in Utila and nine in Cayos Cochinos over maximum periods of 12.4 (2006–2019) and 2.4 (2018–2021) years respectively; and (2) identify the modes of island planar morphological adjustments over these timescales. Our research thus begins to address the geographical Caribbean gap in reef island shoreline change research and discusses the implications of our results within the context of reef island monitoring and futures.

2. Materials and Methods

2.1. Field Sites

The Mesoamerican Barrier Reef (MBR) is the second largest barrier reef system in the world, extending 1000 km from the Yucatan Peninsula to the Honduran Bay Islands in the western Caribbean Sea. Ecosystem services provided by the MBR, primarily from tourism and fishing, directly support several million people along the MBR coastlines [42]. Utila and Cayos Cochinos (Figure 1) are located at the southern end of the MBR and sit atop a 75 km wide continental shelf that runs along the Honduran Caribbean coastline. The region has been considerably less studied than the northern MBR in Belize and Mexico [34,35,38,39,43]. Utila is the smallest of the three Bay Islands that are the central focus of Honduran reef-related tourism and fishing industries. Twelve reef islands (locally termed sand cays) are located off Utila's western coastline. Cayos Cochinos is a Marine Protected Area located approximately 48 km southeast of Utila. The archipelago spans 460 km^2 and is managed by the Honduran Coral Reef Fundación. It comprises 2 larger islands and, currently, 13 smaller reef islands. The majority of Utila and Cayos Cochinos cays are privately owned and uninhabited for most of the year. Exceptions are Suc-Suc and Pigeon Cays in Utila (home to ~500 inhabitants, and Cayo Chachauate in Cayos Cochinos (home to 200 people from the Garifuna community).

Surface waters around Utila and Cayos Cochinos are dominated by the Caribbean Current that enters the Caribbean basin through the Lesser Antilles from the Equatorial Atlantic [44,45] and flows clockwise along the southern Caribbean before turning north-west and exiting through the Yucatan Channel [45,46]. The region is also influenced by a local counter-clockwise gyre at the Nicaraguan coast [47] and a relatively small, cyclonic counter-clockwise current from January to March [48], which lowers sea surface temperatures and enhances coastal upwelling [49]. The climate is dominated by seasonal, easterly trade winds which generate a rainy season between March and September. In winter, prevailing winds shift to northerly and westerly [50]. Despite being within the Atlantic hurricane belt, hurricanes in Utila and Cayos Cochinos are relatively infrequent, particularly outside of the September-November hurricane season [32]. In recent decades, the most notable events have been Hurricanes Mitch in 1998 (a category 5 hurricane that was the deadliest to hit the western hemisphere for two centuries) and Eta (category 4) in 2020.

Honduras has a small tidal range of 0.3–0.5 m, which is dominated by meteorological tides [32,51]. Local rates of sea-level rise are difficult to discern due to a lack of tide gauges in the Western Caribbean. The World Meteorological Organisation estimated sea-level rise in the tropical North Atlantic, including the Honduran coastline, as 3.23 $\pm$ 0.1 mm/yr between 1993 and 2022 [52], but a more conservative estimate from the Puerto Cortes tide gauge averaged 1.8 mm/yr between 1950 and 2009 [53]. Torres and Tsimplis [30] estimated a sea-level rise rate of 1.7 $\pm$ 1.4 mm/yr during 1993 to 2010.

2.2. Island Selection

A total of seven reef islands located off the western coast of Utila and nine in Cayos Cochinos (Figure 1) were chosen for shoreline change analysis. Selection was based on criteria for the islands to be natural, to allow examination of natural reef island behaviour, including that of sediment transport pathways. For this research, natural islands are defined as islands with no visible or known hard infrastructure, such as seawalls, surrounding them that may alter natural sediment production and transport pathways responsible for island evolution [24,54], and/or where buildings occupied <50% of the island. For ease, all islands hereafter are referred to by codes detailed in Table 1. Note that the smallest cay in Utila, attached by a sand bar to a larger island named Little Cay, does not have a documented name so we refer to it as Little Cay A and U7.

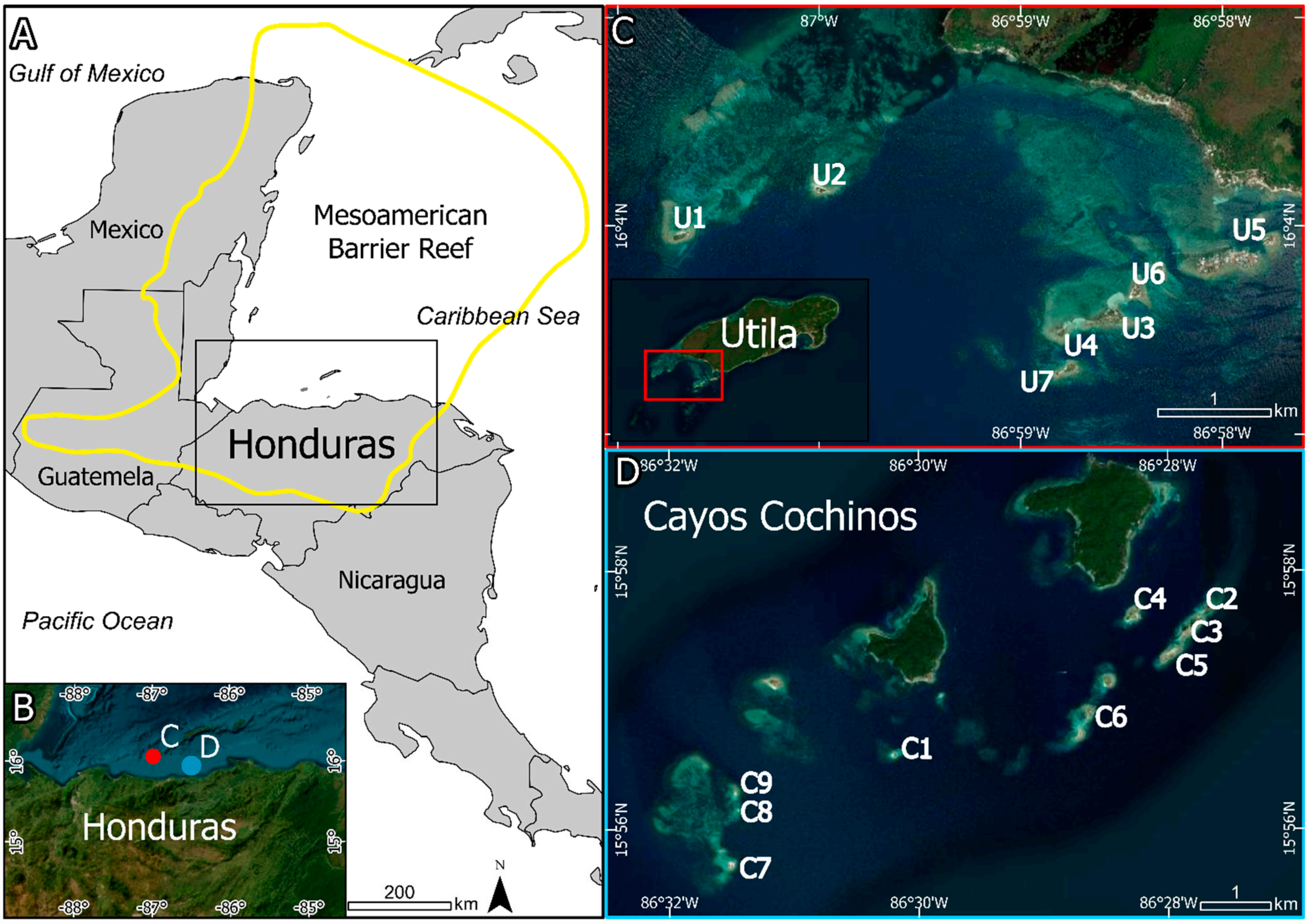

Figure 1. Northern Honduras (**A**,**B**) reef islands subject to shoreline change analysis from Utila (**C**) and Cayos Cochinos (**D**). Utila reef islands are: Sandy Cay (U1), South West Cay (U2), Water Cay (U3), Morgan's Cay (U4), Diamond Cay (U5), Bells Cay (U6), and Little Cay A (U7). Cayos Cochinos Cays are: Paloma (C1), Balfate (C2), Largo Arriba (C3), Borrego (C4), Largo Abajo (C5), Chachauate (C6), Bolanos (C7), Zacate (C8), Timon (C9). Mesoamerican Barrier Reef area represented by yellow outline.

2.3. *Image Georeferencing*

Image analysis was conducted using satellite imagery [55–58] within ArcGIS 10.7. The time period of analysis varied between islands, dependent on image quality control, image availability, and whether there was evidence of notable, anthropogenic management of island vegetation (used as a proxy for island shorelines, see below). Regarding the latter, where a densely vegetated island changed to one with sparse vegetation in straight, unnatural lines, analysis concluded at the last 'natural' image available. Additionally, to be included as a valid image in the analysis, the full vegetation line around each island was required to be fully visible in each image without obstruction from photographic glare. The temporal sequence of the final datasets covered a maximum period of 12 years and 5 months between 2006 and 2019 for Utila (12.4 years). In Cayos Cochinos, imagery was available for all islands for 2 years and 5 months (2.4 years), and additionally for 4 years and 9 months (4.75 years) for C1, C2 and C3 (Table 1).

Table 1. Oldest and most recent satellite image available for selected reef islands, and net study period of shoreline change analysis.

Reef Island	Code	Oldest Shoreline	Most Recent Shoreline	Maximum Study Period	Number of Images Analysed
Utila					
Sandy	U1	06/06/2010	23/01/2019	8 yrs 7 mths	5
Southwest	U2	06/06/2010	23/01/2019	8 yrs 7 mths	4
Water	U3	12/08/2006	23/01/2019	12 yrs 5 mths	6
Morgans	U4	12/08/2006	23/01/2019	12 yrs 5 mths	6
Diamond	U5	12/08/2006	30/06/2016	9 yrs 9 mths	5
Bells	U6	12/08/2006	06/07/2013	6 yrs 9 mths	4
Little Cay A	U7	12/08/2006	21/01/2019	12 yrs 5 mths	6
Cayos Cochinos					
Palamo	C1	31/05/2016	17/03/2021	4 yrs 9 mths	4
Balfate	C2	31/05/2016	17/03/2021	4 yrs 9 mths	3
Largo Arriba	C3	31/05/2016	17/03/2021	4 yrs 9 mths	3
Borrego	C4	17/10/2018	17/03/2021	2 yrs 5 mths	2
Largo Abajo	C5	17/10/2018	17/03/2021	2 yrs 5 mths	2
Chachauate	C6	17/10/2018	17/03/2021	2 yrs 5 mths	2
Bolanos	C7	17/10/2018	17/03/2021	2 yrs 5 mths	3
Zacate	C8	17/10/2018	17/03/2021	2 yrs 5 mths	3
Timon	C9	17/10/2018	17/03/2021	2 yrs 5 mths	3

Satellite images were georeferenced using a range of uniformly distributed, permanent natural (e.g., beachrock and reef geomorphology visible through the water surrounding each island, particularly in nearshore areas) and anthropogenic (e.g., corners of buildings, jetties) control points that were consistent between images. As is common in reef island imagery, conventional permanent reference points, such as surveyed datum points were not available in our imagery [23] and island vegetation obscured many permanent features on the islands [27,59,60]. Thus, the use of both geomorphic and anthropogenic features provided sufficient ground points to ensure accurate georectification. The control points and a first-order polynomial transformation were used to align the oldest image in each island set to ESRI 2021 Basemap data in ArcGIS, and then each subsequent image to this oldest image. The georectification error ranged between 0.13 to 1.02 (S.I.1).

2.4. Shoreline Digitisation

For decadal research, the vegetation edge has been deemed the most reliable indicator of medium-term island stability [27,59]. This proxy is often the only island feature consistently detectable in all reef island imagery, sitting above the high-water mark, thus allowing the interpretation to be repeated throughout the dataset. In contrast, the toe of the beach, for example, is not always accurately identifiable due to inconsistency in the timing of satellite image capture relative to tidal stage. Consequently, in this research, we use the vegetation line to represent the stable island perimeter and as a proxy for island shorelines. In each image, the vegetation line was digitised at a uniform 1:250 scale to capture small-scale detail provided by island vegetation. The process was completed by a single researcher to limit subjectivity [21,23,59,61].

2.5. Shoreline Error

The positional uncertainty of each digitised shoreline was calculated using the Root Mean Square Error (RMSE) [62,63] approach that considers three sources of error commonly recognised in shoreline change research: (i) georectification error (calculated within ArcGIS, S.I.1.), (ii) satellite image pixel size, and (iii) human digitisation error. The latter was calculated by digitising the same segment of U3 shoreline ten times and averaging ten measured distances between the nearest and furthest lengths along the segment. Human digitisation error was calculated as 0.23 m, pixel size ranged from 0.16 to 0.50 m, and overall RMSE ranged from 0.17 to 0.61 m (S.I.1; [64]).

2.6. Digital Shoreline Analysis System Data Processing

The Digital Shoreline Analysis System (DSAS) is an ArcGIS extension commonly used in coastal change research [64] and was used here to analyse changes in shoreline position between images, following Ford [59]. A baseline was constructed at a constant distance offshore of the vegetation edge around each island. DSAS then cast transects at 4 m intervals from this baseline that intersected with all vegetation lines for each island. This close transect spacing was chosen to capture any dynamic planform changes in shoreline position at a scale that could be consistent for both large and small islands. A larger spacing may have led to under sampling, and a smaller spacing may have led to transect overlap and duplicate sampling on shoreline positions, particularly along curved sections. The transects were inspected and edited to ensure they were all perpendicular to the shorelines they were intersecting. Consequently, while originally spaced at 4 m around the baseline, the final points of intersection between transects and the vegetation lines may have deviated slightly from 4 m. Some additional transects were also manually added where there were substantial changes in the vegetation edge between the 4 m intervals. DSAS analysis was then run for each island to calculate change-based statistics on the seaward intersections between the transects and shorelines.

2.7. Shoreline Change Statistics

Three statistical measures of linear change in the vegetation edge from the DSAS analysis were considered to interpret shoreline behaviour. First, for all islands, net shoreline movement (NSM, m) represented the distance between the oldest and the most recent shorelines in the dataset and provided data comparable to that used to examine anecdotal evidence shoreline change [59]. Secondly, for all Utila islands, rates of shoreline change were calculated using weighted linear regression (WLR, m yr^{-1}) at a 95% confidence level (2o/1.92 SD). WLR calculated the annualised rates of shoreline change while accounting for the positional uncertainty of each shoreline, giving larger weighting to shorelines with lower uncertainty and vice versa, thus providing a statistically robust measure of shoreline change [65]. Thirdly, for Cayos Cochinos islands, where the data spanned a shorter time period (2018–2021, Table 1), shoreline change rates were calculated from end-point measurements (EPR, m/yr, 95% CI) [24,66], which normalised net shoreline movement by time. A total of 3 reef islands in Cayos Cochinos also had data available from 2016 which were additionally analysed over the 5-year period. For each DSAS statistic, transects were classified as accretionary or erosive, depending on whether NSM, WLR, and EPR values were greater or lesser than the mean island RMSE for respective islands (S.I.1). Transects with values within an interval $\pm$ mean island RMSE were classified as stable.

To examine overall island area change, the island shorelines were converted into polygons from which area statistics were extracted. For each island, area change was then calculated between each time point and as overall net change between the youngest and most recent shorelines. Consistent with recent studies, a proportional change threshold of $\pm$ 3% was used to define whether the island areal change was significant, and classify the islands as either accretionary, stable, or erosive [10,23,29,60]. Finally, in the Pacific and Indian Oceans, island size has been recognised as a key driver of island shoreline change behaviour [11,67,68]. Thus, linear regression analysis was used to analyse the relationship between island size (defined as original island area) and the above shoreline change statistics.

3. Results

3.1. Utila Reef Island Shoreline Change

In Utila, data were available for a maximum period of 12.4 years from August 2006 to January 2019. Within this time, and over their respective periods, 5 of the 7 Utila reef islands increased in area, ranging from a 10% area increase (859 m^2) on U6 to 13% (817 m^2) on U5. Just 2 of the 7 islands, U7 and U2, experienced net area decreases of −5% (−28 m^2) and −1% (−26 m^2) respectively. However, only U7 met the ± 3% change threshold used to define marked island erosion. U2 was therefore classified as stable (Table 2). Aggregated across all cays, net island area increased by 3733 m^2 (9%).

Table 2. Area change experienced by Utila reef islands over respective study periods. Islands are ordered from smallest to largest. * Island behaviour categorised based on ±3% area change threshold. Red text highlights a reduction in island area of all islands between March and July 2013. Periods where no shoreline change data were available are marked with −.

Utila Reef Island	Study Period	Oldest Area (m^2)	Most Recent Area (m^2)	Area Percent Change (%)						Overall Net Change (%)	Overall Island Behaviour *
				Aug 2006–Jun 2010	Jun 2010–Mar 2013	Jun 2010–Jul 2013	Mar 2013–Jul 2013	Jul 2013–Jun 2016	Jun 2016–Jan 2019		
U7	2006–2019	562	535	−3%	0%	–	−8%	7%	0%	−5%	Eroded
U4	2006–2019	2225	2491	4%	10%	–	−6%	1%	4%	12%	Accreted
U1	2010–2019	2551	2869	–	14%	–	−18%	18%	3%	13%	Accreted
U2	2010–2019	4839	4813	–	–	−4%	–	8%	−5%	−1%	Stable
U5	2006–2016	6254	7071	4%	9%	–	−1%	1%	–	13%	Accreted
U6	2006–2013	8695	9554	3%	8%	–	−1%	–	–	10%	Accreted
U3	2006–2019	14,491	16,018	3%	8%	–	−6%	1%	4%	11%	Accreted

Of the 3 islands with data spanning the entire 12.4-year period, U4 and U3 followed similar evolutionary trajectories, with their areas increasing throughout the period by similar proportions, except for an area decrease between March and July 2013. Conversely, U7 decreased in area throughout the period, however the magnitude of decrease was greatest in 2013 (Table 2).

Considering DSAS data, 708 transects were cast around the Utila islands. Comparing the distance between the oldest and most recent shorelines, 419 transects (59.1%) had a net positive distance greater than the respective mean island RMSE and were classified as accretionary. A total of 248 transects (35%) had a net negative distance and were classified as erosive, and 42 (5.9%) were classified as stable (Table 3). Across all islands, average net shoreline movement (NSM) was 1.2 ± 1.2 m (Figure 2, Table 3). Five of the seven islands had a mean positive NSM. They ranged from 1.0 ± 5.0 m on U1 to 2.2 ± 4.1 m on U3, and a greater proportion of accretionary transects than erosive. Conversely, U7 and U2 were the only 2 cays with mean negative NSM values of −0.3 ± 1.1 m and −0.03 ± 3.5 m respectively, and a greater proportion of erosive transects than accretionary. For all seven islands, the mean NSM of transects with a positive (accretionary) distance was greater than the mean NSM of transects with a negative (erosive) distance (Table 3). Reflecting trends in area change, U5 had the highest percentage of accreting transects (87.7%). U7 had the highest proportion of stable transects (25.8%) and U2 had the greatest percentage of erosive transects (51.3%).

Considering the rate data, 275 (38.8%) of transects were classified as accretionary, 98 (13.8%) as erosive, and 336 (47.4%) as stable (Table 3). Mean WLR for Utila islands was 0.1 ± 0.1 m/yr and ranged from 0.0 ± 0.3 m/yr on U2 to −0.0 ± 0.1 m/yr on U7—the only island with a mean negative WLR (Table 3). For all five accreting islands, the mean WLR of transects with positive (accretionary) WLR values was greater than that of transects with negative values (Table 3). Likewise, all cays with exception of U7 had a greater proportion of accretionary than erosive transects. Although U7 is classified erosive, we note that proportional area decrease, mean NSM, and mean WLR for this island were all of lower magnitude than the respective statistics for the five accreting cays. Additionally, 100% of

WLR transects for U7 were classified as stable. Thus, overall, the results indicate marked island accretion in Utila between 2006 and 2019.

Table 3. Shoreline change responses and DSAS statistics for Utila reef islands. Islands ordered from smallest to largest. * Indicates islands classified as experiencing significant erosion, and ** significant accretion. Cays without * are classified as stable. Mean WLR error is represented by uncertainty of the average rate using reduced n, as calculated by DSAS [69]. Mean values calculated using all transects irrespective of classification.

			Net Shoreline Movement						Weighted Linear Regression					
Utila Reef Island	**Study Period**	**Transect Count**	**Mean ± SD (m)**	**Mean Positive Distance ± SD (m)**	**Mean Negative Distance ± SD (m)**	**Accretionary Transects (%)**	**Stable Transects (%)**	**Erosive Transects (%)**	**Mean ± Error (m/yr)**	**Mean Positive WLR ± SD (m/yr)**	**Mean Negative WLR ± SD (m/yr)**	**Accretionary Transects (%)**	**Stable Transects (%)**	**Erosive Transects (%)**
U7 **	*2006–2019*	31	−0.3 ± 1.1	0.9 ± 0.6	−0.9 ± 0.7	25.8	25.8	48.4	−0.0 ± 0.1	0.1 ± 0.0	−0.1 ± 0.1	0.0	100.0	0.0
U4 *	*2006–2019*	68	1.8 ± 4.2	3.0 ± 4.3	−1.6 ± 1.4	66.7	15.9	17.4	0.1 ± 0.1	0.2 ± 0.4	−0.1 ± 0.1	21.7	68.1	10.1
U1 *	2010–2019	87	1.0 ± 5.0	4.4 ± 4.0	−3 ± 2.5	51.7	4.6	43.7	0.1 ± 0.3	0.4 ± 0.3	−0.4 ± 0.3	35.6	39.1	25.3
U2	2010–2019	117	−0.0 ± 3.5	3.0 ± 2.0	−2.8 ± 2.1	44.4	4.3	51.3	0.0 ± 0.3	0.3 ± 0.2	−0.3 ± 0.2	30.8	49.6	19.7
U5 *	2006–2016	75	1.8 ± 2.9	2.9 ± 1.6	−2.7 ± 2.7	78.7	4.0	17.3	0.2 ± 0.2	0.3 ± 0.2	−0.3 ± 0.2	50.7	41.3	8.0
U6 *	2006–2013	134	2.0 ± 4.7	4.9 ± 3.5	−2.3 ± 2.1	59.0	3.0	38.1	0.3 ± 0.2	0.7 ± 0.4	−0.3 ± 0.2	53.0	33.6	13.4
U3 *	*2006–2019*	196	2.2 ± 4.1	4.2 ± 3.3	−1.9 ± 1.6	66.3	3.6	30.1	0.2 ± 0.2	0.3 ± 0.3	−0.2 ± 0.2	42.9	45.9	11.2

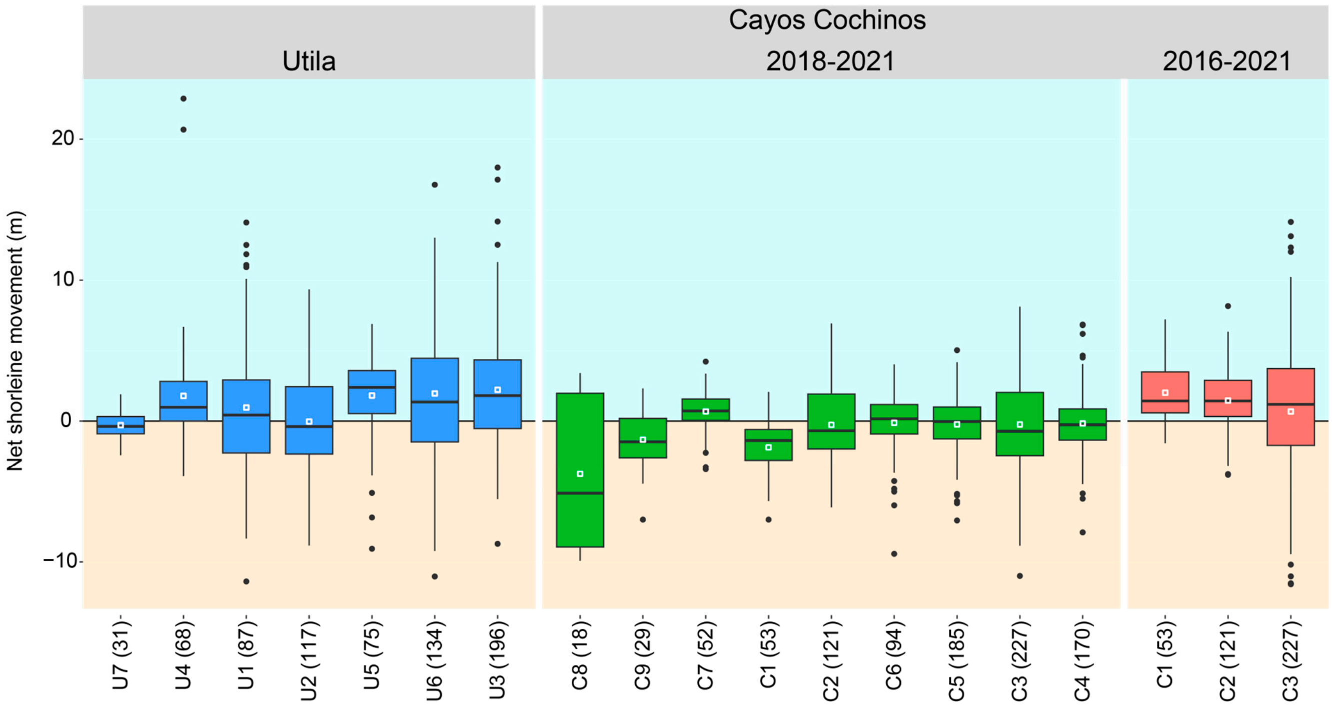

Figure 2. Box (50% quartile) and whisker (95% quartile) plots representing net shoreline movement (NSM, m) transect data for the respective maximum study periods of Utila and Cayos Cochinos reef islands (Table 1). White squares represent mean NSM (m) for each island. Reference line at 0 m NSM represents island stability and, either side, positive values represent island accretion, and negative values represent island erosion. Numbers in brackets equal transect sample size. Islands are ordered by ascending size.

3.2. *Cayos Cochinos Reef Island Shoreline Change*

Between 2018 and 2021, 8 of the 9 islands in Cayos Cochinos decreased in area, ranging from −1% (−229 m^2) net change on C4 to −76% (−126 m^2) on C8 (Table 4). Marked area decreases (> ± 3%), however, were only observed on islands C1, C8 and C9, leaving

5 islands classified as stable. C7 was the only island to increase in size (9%, 94 m^2). Overall, net island area change was non-significant, decreasing by just 2% (1364 m^2) over 2.4 years (Table 4).

Table 4. Area change on Cayos Cochinos reef islands over respective study periods. * Island behaviour categorised based on ±3% area change threshold.

Cayos Cochinos Cay	Island Area (m^2)			Area Percent Change %			Overall Island Behaviour 2018–2021 *
	2016	2018	2021	2016–2018	2016–2021	2018–2021	
C1	974	1493	1255	53%	29%	−16%	Eroded
C2	4646	5292	5153	14%	11%	−3%	Stable
C3	19,506	20,372	20,120	4%	3%	−1%	Stable
C8		165	39			−76%	Eroded
C9		356	253			−29%	Eroded
C7		1050	1144			9%	Accreted
U6		5082	4981			−2%	Stable
C5		16,184	15,915			−2%	Stable
C4		21,979	21,750			−1%	Stable

Of the 949 transects cast around the Cayos Cochinos islands, 366 (38.6%) had net shoreline movement > mean island RMSE and were classified as accretionary, 476 (50.2%) were classified as erosive, and 107 (11.3%) as stable. Individually, seven islands had a greater proportion of transects classified as erosive than accretionary. Five islands had >50% transects classified as erosive (Table 5). Mean NSM was negative (erosive; −0.8 ± 1.3 m;) for 8 of the 9 islands, ranging overall from −3.8 ± 5.3 m on C8 to 0.7 ± 1.5 m on C7 (Table 5, Figure 2).

Table 5. Shoreline change responses and DSAS statistics for Cayos Cochinos reef islands. * Indicates islands classified as experiencing significant erosion, and ** significant accretion. Cays without * are classified as stable. Mean EPR Uncertainty is represented by summation of squares calculated by DSAS [69]. Mean values calculated using all transects irrespective of classification.

			Net Shoreline Movement						End Point Rate					
Cayos Cochinos Cay	Study Period	Transect Count	Mean ± SD (m)	Mean Positive Distance (m)	Mean Negative Distance (m)	Accretionary Transects (%)	Stable Transects (%)	Erosive Transects (%)	Mean ± Error (m)	Mean Positive WLR (m/yr)	Mean Negative WLR (m/yr)	Accretionary Transects (%)	Stable Transects (%)	Erosive Transects (%)
C1 **	2016–2021	53	2.0 ± 2.18	2.6 ± 1.9	−0.6 ± 0.5	77.4	9.4	13.2	0.4 ± 0.07	0.5 ± 0.4	−0.1 ± 0.1	54.7	41.5	3.8
C2 **		121	1.5 ± 2.36	2.4 ± 1.7	−1.8 ± 1.0	74.4	5.0	20.7	0.3 ± 0.09	0.5 ± 0.4	−0.4 ± 0.2	43.8	45.5	10.7
C3 **		227	0.7 ± 4.46	3.6 ± 2.7	−3.3 ± 3.1	54.6	6.2	39.2	0.1 ± 0.11	0.8 ± 0.6	−0.7 ± 0.6	41.9	33.0	25.1
C1 *	2018–2021	53	−1.9 ± 2.02	1.0 ± 0.8	−2.3 ± 1.8	9.4	9.4	81.1	−0.8 ± 0.14	0.4 ± 0.3	−0.9 ± 0.7	7.5	24.5	67.9
C2		121	−0.3 ± 2.8	2.5 ± 1.8	−2.2 ± 1.4	36.4	9.1	54.5	−0.1 ± 0.22	1.1 ± 0.7	−0.9 ± 0.6	30.6	21.5	47.9
C3		227	−0.2 ± 3.49	3.1 ± 2.2	−2.6 ± 2.0	38.3	7.5	54.2	−0.1 ± 0.27	1.3 ± 0.9	−1.1 ± 0.8	34.8	17.2	48.0
C8 *		18	−3.8 ± 5.32	2.3 ± 0.7	−7.6 ± 2.4	38.9	0.0	61.1	−1.6 ± 0.15	0.9 ± 0.3	−3.1 ± 1.0	38.9	0.0	61.1
C9 *		29	−1.3 ± 2.04	0.9 ± 0.9	−2.3 ± 1.5	17.2	20.7	62.1	−0.5 ± 0.17	0.4 ± 0.3	−1.0 ± 0.6	13.8	24.1	62.1
C7 **		52	0.7 ± 1.52	1.3 ± 1.0	−1.5 ± 1.2	65.4	15.4	19.2	0.3 ± 0.14	0.5 ± 0.4	−0.6 ± 0.5	50.0	36.5	13.5
C6		94	−0.1 ± 2.14	1.3 ± 1.0	−1.8 ± 1.9	46.8	14.9	38.3	−0.1 ± 0.18	0.6 ± 0.4	−0.7 ± 0.8	36.2	33.0	30.9
C5		185	−0.2 ± 1.95	1.3 ± 1.0	−1.7 ± 1.5	41.6	12.4	45.9	−0.1 ± 0.12	0.5 ± 0.4	−0.7 ± 0.6	35.1	24.3	40.5
C4		170	−0.2 ± 2.15	1.7 ± 1.6	−1.5 ± 1.4	37.1	13.5	49.4	−0.1 ± 0.17	0.7 ± 0.7	−0.6 ± 0.6	26.5	35.3	38.2

Regarding the rate data, 301 transects (31.7%) were classified as having an accretionary EPR, 408 (43%) as erosive, and 240 (25.3%) as stable (Table 5). In total, 3 of the nine islands had >60% of transects classified as erosive. Just 1 island had >50% of transects classified as accretionary. Mean EPR across all islands was −0.3 ± 0.6 m/yr, ranging from −1.6 ± 0.2 m/yr on C8 to 0.3 ± 0.1 m/yr on C7, reflecting trends in island area change (Table 4). C7 was the only island with mean positive (accretionary) NSM and EPR values.

For C1, C2 and C3, data were available for an additional timepoint of May 2016, which when considered, altered the trends identified in island behaviour over the shorter 2018 to 2021 period. Between 2016 and 2021 all 3 islands showed a significant increase in area, and mean NSM and EPR for all 3 islands reversed from being negative between 2018–2021, to positive (Tables 4 and 5). The proportion of erosive and accretionary transects (NSM and WLR) also reversed for all 3 cays, from having a higher proportion of erosive transects than accretionary transects between 2018–2021, to a greater proportion of accretionary transects 2016–2021 (Table 5).

3.3. Relationships between Island Shoreline Change Behaviour and Island Size

Due to variation in study periods, relationships between island size and shoreline change at Utila could only be analysed with WLR. While there is a weak, positive correlation between original island size and WLR for Utila (r^2 = 0.32; Figure 3A), analysis of this data using a 95% confidence level revealed no significant relationship (linear regression: $F(1, 5) = 2.40$, $p = 0.42$) between island size and mean WLR.

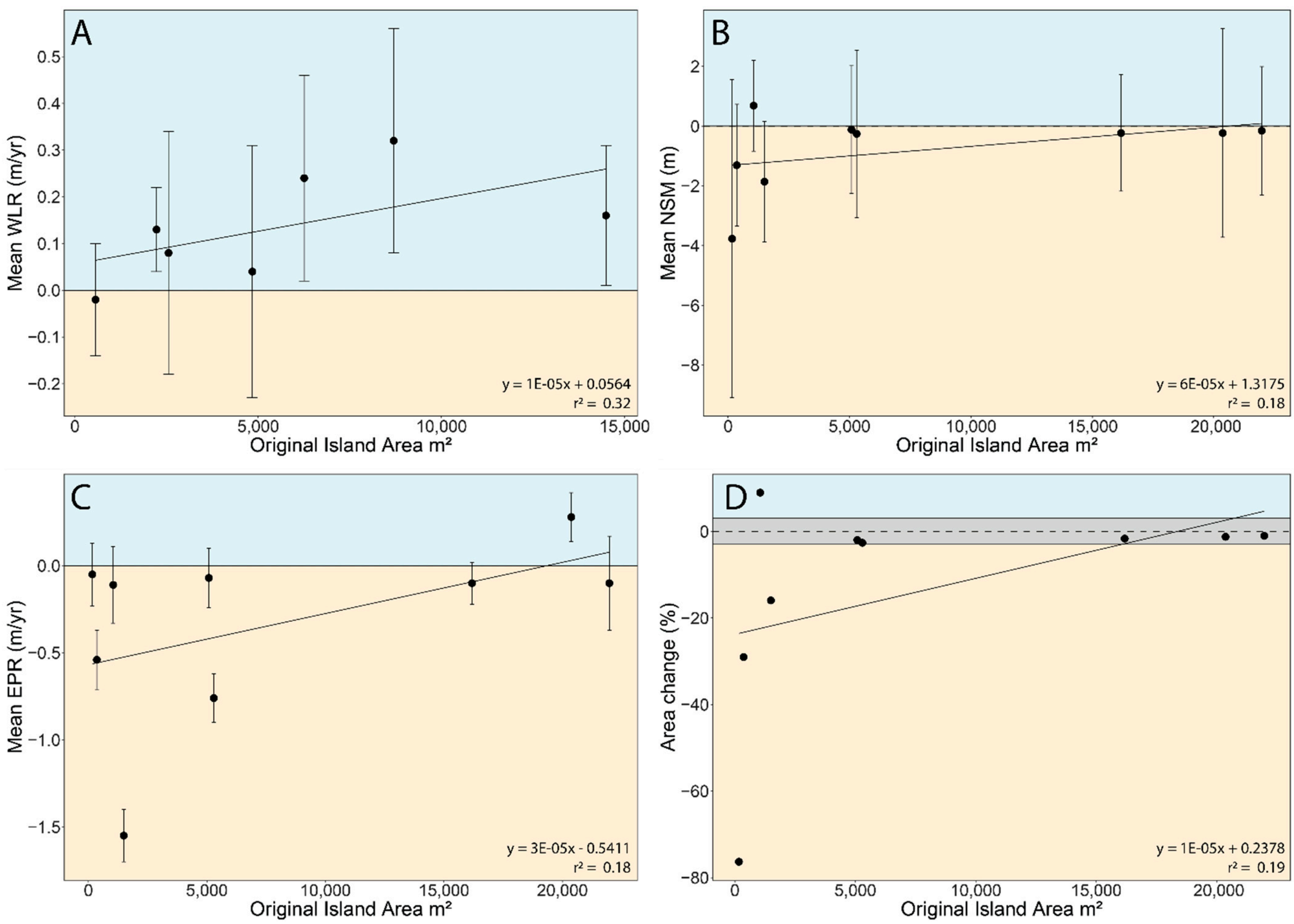

Figure 3. Original area of reef islands in Utila (**A**) and Cayos Cochinos (**B**–**D**) compared against (**A**) mean island weighted linear regression (WLR) in Utila (m/yr); error bars represent uncertainty of the average WLR using reduced n [69]. In Cayos Cochinos, reef island area was compared against

(**B**) mean island net shoreline movement (NSM, m; error represented by standard deviation), (**C**) mean end-point ratio (EPR, m/yr; error represented by summation of squares calculated by DSAS), and (**D**) proportional area change between 2018 and 2021 (%), where grey shading represents a ±3% threshold of island stability). Black lines represent regression (y = mx + c) between respective variables; dashed lines represent complete island stability (0), either side of which represents either island erosion or accretion.

For the Cayos Cochinos data between 2018 to 2021, no significant relationship (95% confidence) was identified between island size and mean EPR (Figure 3B, $r^2 = 0.18$; linear regression: $F(1, 7) = 1.55$, $p = 0.06$), mean NSM (Figure 3C, $r^2 = 0.18$; linear regression: $F(1, 7) = 1.58$, $p = 0.06$), or proportional area change (Figure 3D, linear regression: $r^2 = 0.19$; linear regression: $F(1, 7) = 1.74$, $p = 0.07$). Although sample size is small, all 3 graphs (Figure 3B–D) do suggest that islands <5000 m^2 show more variability in rates and magnitudes of change than those >5000 m^2.

3.4. Modes of Reef Island Planar Change

Net changes in island area often mask smaller-scale and more variable shoreline changes occurring around each island. This local variation is expressed as island planform morphological adjustments that are represented by a range of modes of island change. Modes of change were identified for each island based on data from reef islands in the Indian and Pacific Oceans (Table 6; Figure 4, [11,23,28]). Where there was evidence of island behaviour reflecting more than one mode, islands were assigned a primary (dominant) mode, and a secondary (less dominant mode) (Table 6).

Table 6. Primary and secondary modes of planar change exhibited by reef islands in Utila and Cayos Cochinos. Note for Cayos Cochinos that island behaviour is considered for all islands between 2018 and 2021. Total count represents all islands that exhibit a behaviour as either their primary or secondary mode.

		Utila		Cayos Cochinos		All Islands		
	Modes	**1st**	**2nd**	**1st**	**2nd**	**Total**	**%**	**Characteristics of Geomorphic Change**
Accretion	Accretion	1	-	1	-	5	31.25	Accretion around entire permieter
	Lagoonwards accretion	2	-	-	-			Stability of oceanward shoreline and accretion of lagoonwards shoreline
	Oceanward accretion	-	1	-	-			Stability of lagoonward shoreline and accretion of oceanward shoreline
Erosion	Contraction	-	-	3	-	5	31.25	Erosion around entire permieter
	Oceanward retreat	1	-	-	1			Stability of lagoonward shoreline and erosion of oceanward shoreline
Migration	Lagoonwards migration	-	-	1	2	6	37.50	Erosion of oceanward shoreline and accretion of lagoonward shoreline
	Oceanward migration	-	-	1	-			Erosion of lagoonward shoreline and accretion of oceanward shoreline
	Eastwards migration	1	-	-	-			Eastwards migration of island along reef platform
	Northern migration	-	-	-	1			Northern migration of island along reef platform
Extremity change	Lateral extension	1	4	-	-	8	50.00	Accretion of island spits of extremities (e.g., tips)
	Lateral contraction	-	-	-	3			Erosion of island spits of extremities (e.g., tips)
Rotation	Rotation	-	1	-	1	2	12.50	Island rotates around a central pivot position on reef platform
No mode	Stable	1	-	3	-	4	25.00	No evident large scale shift in island footprint on reef platform

Considering all Utila islands, no overall dominant mode of planform change was identified, with every island having a different primary mode of change, except for U3 and U6 which both accreted lagoonwards (Figure 4). In Cayos Cochinos, C1, C8 and C9 all experienced contraction (Figure 4). Across both sites, 25% of all cays were classified as 'stable'; these included the 3 cays in Cayos Cochinos with the least significant areal change, (C3, C4 and C5, Figure 4) and U2 in Utila (Figure 4). On these stable islands, shoreline change was still highly variable, but occurred at very small scales around the entire island, thus resulting in apparent stability of the overall island footprint atop the reef platform(s).

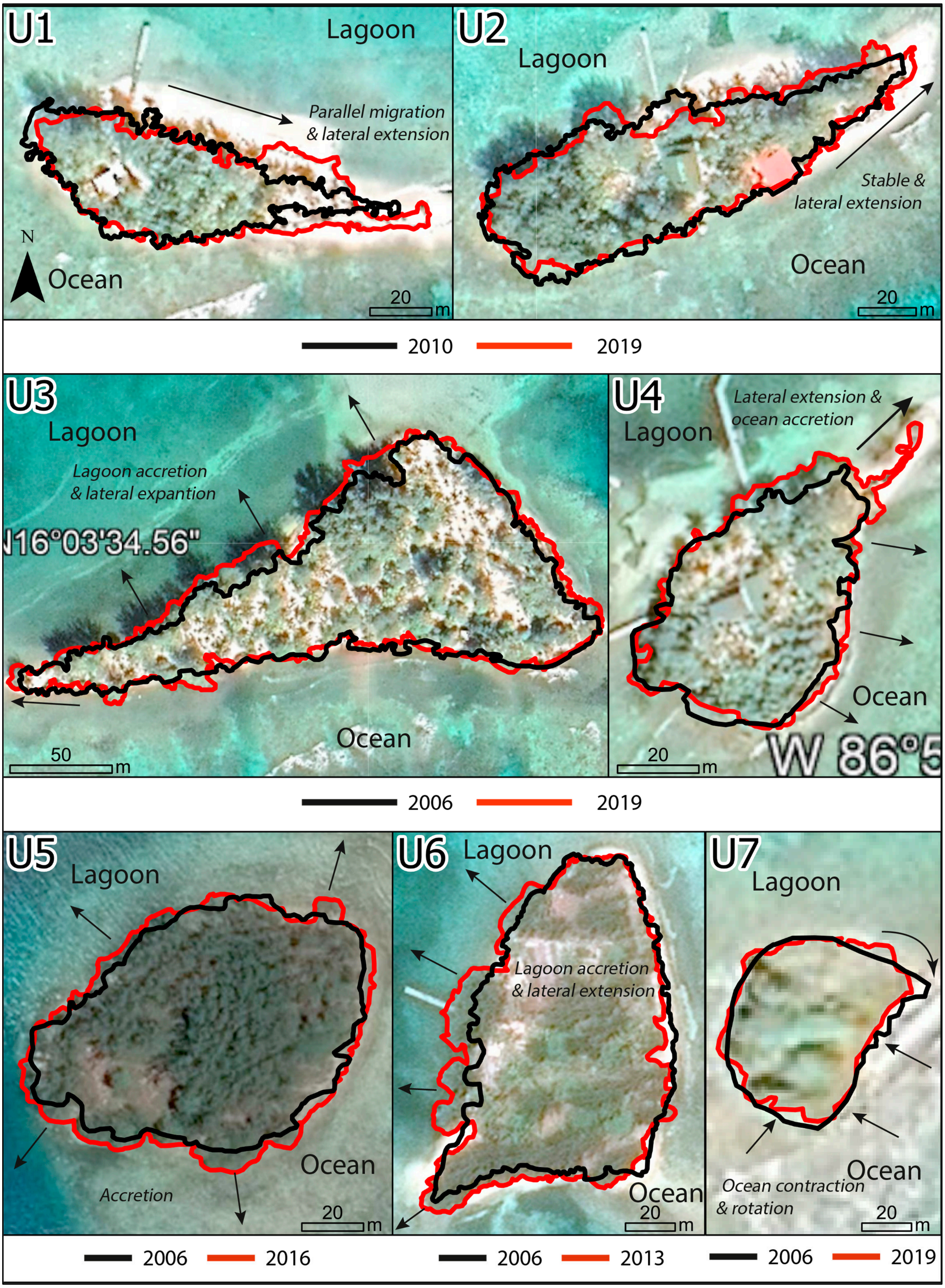

Figure 4. *Cont.*

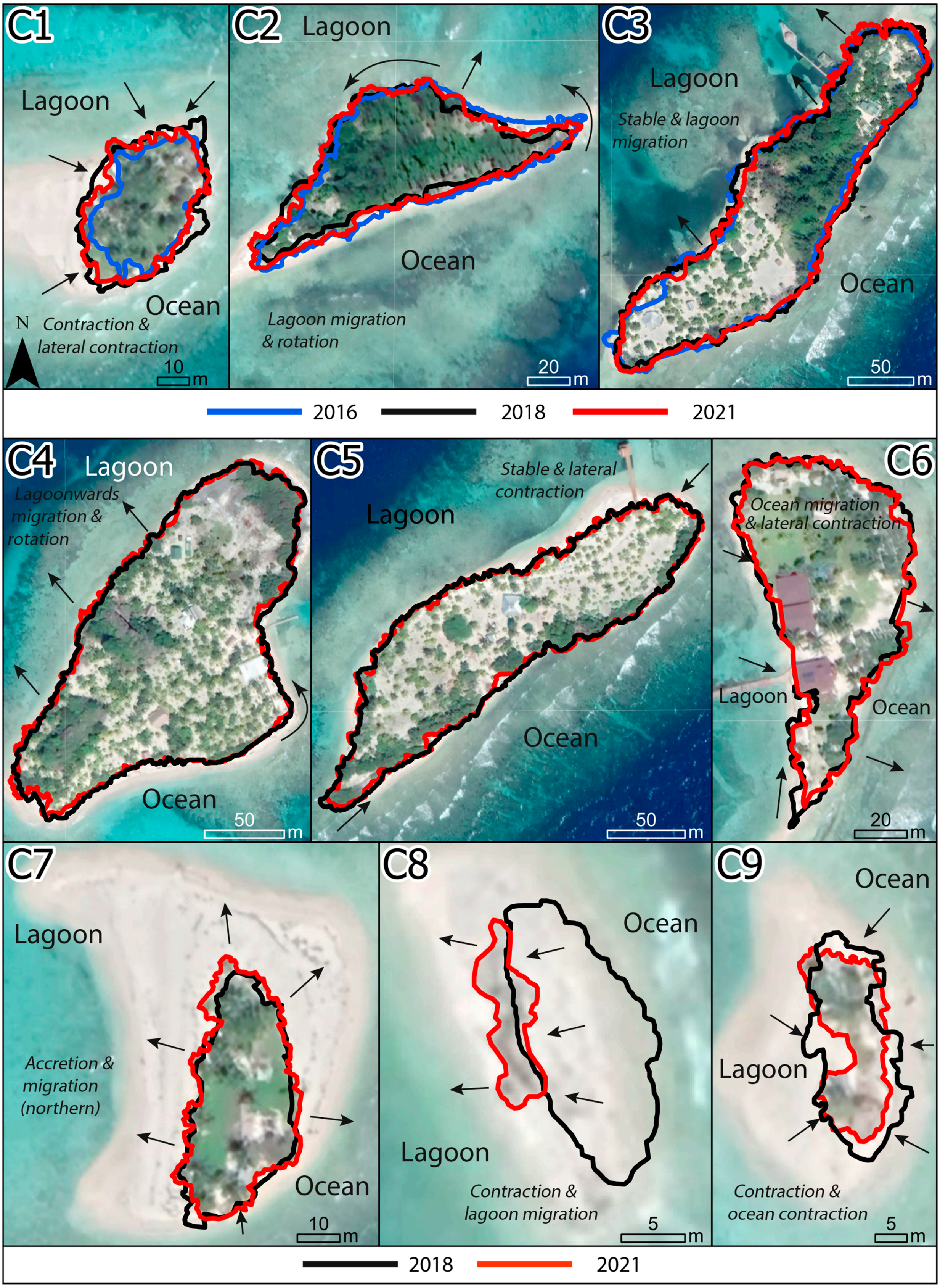

Figure 4. Geomorphic modes of planar change on the seven Utila and nine Cayos Cochinos reef islands. Utila islands are Sandy Cay (**U1**), South West Cay (**U2**), Water Cay (**U3**), Morgan's Cay (**U4**),

Diamond Cay (**U5**), Bells Cay (**U6**), Little Cay A (**U7**). Cayos Cochinos islands are Paloma (**C1**), Balfate (**C2**), Largo Arriba (**C3**), Borrego (**C4**), Largo Abajo (**C5**), Chachauate, (**C6**), Bolanos (**C7**), Zacate (**C8**), Timon (**C9**). Arrows represent the direction of shoreline change. Modes of shoreline change are identified on each panel, as are the oceanward (ocean) and lagoonward (lagoon) sides of each island.

3.5. Lateral Change (Spits and Extremities)

The secondary modes of island change revealed additional trends in the data, including lateral change being the overall dominant mode of island evolution. Across the dataset, 50% of all islands were identified as exhibiting lateral extension or contraction as either the primary or secondary mode of change (Table 6). U4 (Figure 4) was the only island with a true spit. However, consistent with site-specific trends, U1, U3 and U6 (Figure 4) in Utila all experienced notable extremity widening or lengthening as secondary modes of change, as well as U2 (Figure 4) despite having a 'stable' island body. Conversely, in Cayos Cochinos, C1, C5, and U6 (Figure 4) experienced notable extremity contraction between 2018 and 2021.

3.6. Migration

Island migration (referring to a shift in the overall position of the reef island on the reef platform, Table 6) was the second most common mode of shoreline change, identified on six of the sixteen islands. Five of these islands were in Cayos Cochinos, making it the most common mode at this site, considering primary and secondary modes of change. The direction of migration was predominately lagoonwards (e.g., C2, Figure 4), but also occurred oceanwards (U6, Figure 4), parallel along the reef platform (U1, Figure 4), and in a northerly direction (C7, Figure 4).

4. Discussion

We examined the shoreline change of 16 reef islands across Utila and Cayos Cochinos, Honduras during a period of regional sea-level rise and coral reef degradation. In Utila, the marked accretion identified for five of the seven reef islands was consistent with the behaviour of many Pacific and Indian Ocean reef islands in recent decades [21,23–25,27,28,70]. Observing these overall accretionary trends, we note that the aggregated 9.4% net island area increase likely underrepresents the total area increase of the Utila cays between 2006 and 2019 due to the absence of data for the full period for 4 of the 7 islands. Thus, our data may represent a positive outlook for reef island future physical resilience and persistence.

Aggregated data for Cayos Cochinos also presents an optimistic outlook for reef island futures, with the net island area change of <3% over 2.4 years suggesting a trend of island stability. However, the overall area change masks less positive nuances within the data, including significant area decrease of C1, C8, and C9. Additionally, DSAS data revealed mean negative NSM and EPR for eight of nine islands. These data are more indicative of island instability and erosive trends, and island behaviour more consistent with the substantial, but longer-term erosion of other sites in the Caribbean [38,39], and Pacific [22]. Verbal communication with scientists, and island inhabitants from the Garifuna Community in Cayos Cochinos also suggest a long-term concern regarding erosion observed throughout the archipelago. Specifically, Cayo Arena was reported as having 'not been seen' in two years (nor in satellite imagery), and Cayo Gallo as recently having lost its last remaining palm tree and vegetation, hence not being included in this analysis. These reports are consistent with the 75% area reduction of C8 between 2018 and 2021, and thus suggest that short-term erosive trends in Cayos Cochinos should not be overlooked within the context of stable net island change.

4.1. Modes of Change

Together, the area change and DSAS data reflect the reality that shoreline evolution is not consistent around each reef island but varies in magnitude and direction (accretion and/or erosion) around the entire shoreline. This variation ultimately determines the overall mode of shoreline change behaviour for each island. From examining both primary and secondary modes of change, lateral change was identified as the most common mode of island evolution across Utila and Cayos Cochinos. The dominance of this mode supports global research suggesting that island spits and extremities are the most dynamic part of reef islands [21,27,28,39]. Although the magnitudes of lateral change recorded here were relatively low, we suggest this reflects the shorter observation period of this research compared to other studies. For example, the greatest lateral change observed was a c. 23 m long spit that appeared between 2016 and 2019 on U4, and disproportionately contributed to the island's high mean NSM and WLR (Figure 4). Yet, similar spits in the Indian and Pacific Oceans have extended by up to 100 m, but over multidecadal timescales [23,28,60,61,71].

Lagoonwards migration as the second most common mode of island change is also consistent with reef island behaviour elsewhere within the Caribbean. Indeed, oceanward erosion and leeward shoreline accretion were prominent modes of island change in Belize between 1960 and 2012 [38,39]. Surprisingly, however, our analysis revealed no direct evidence of island aggregation and break up, nor formation, as has occurred in the Indian and Pacific Oceans, albeit over longer-time periods [11,21,25,28,70]. Nonetheless, considerable variability in the magnitude, direction and modes of reef island change suggests that the reef islands in this study are highly dynamic and diverse in their evolutionary behaviour, just like their Indo-Pacific counterparts.

4.2. Effect of Island Size on Island Evolutionary Behaviour

The lack of significant relationships between island size and shoreline change behaviour in Utila and Cayos Cochinos is inconsistent with research revealing island size as a control factor on reef island [11,68] evolution: typically, larger reef islands are more stable than smaller islands [11,68]. Most notably, the largest island in Utila, U3, had the highest mean NSM and contributed to 41% of the net Utila island area increase (Tables 2 and 3). In contrast, the aggregated data from Cayos Cochinos does suggest some effect of size on island behaviour. Here, the four smallest cays (all <1500 m^2) experienced the largest proportional changes in island area, while the largest cay, C4, experienced the smallest proportional areal decrease (Table 4). We also note that U7, the smallest Utila island by an order of magnitude, was the only island to experience significant erosion. These examples suggest that island size should not be disregarded as a control on Honduran reef island behaviour.

In examining the island sizes, we also identify that Caribbean reef islands may, on average, be smaller than their Indo-Pacific counterparts—a characteristic that could explain the lack of significant relationships between island size and shoreline change in this study. It is also a notable consideration given the smaller size of reef islands in nearby Belize [39], and global predictions that the smallest reef islands will be the most vulnerable to environmental change and erosion [11]. Indeed, all reef islands in this study were less than half of the threshold size (<50,000 m^2 or 5 Ha) proposed by Duvat [11], in a global review, to classify the smallest, most unstable reef islands. The large diversity in the magnitude, direction and modes of island planform change exhibited by islands in this study are consistent with typical 'small island behaviour' [11]. Yet, conversely, many of these Honduran cays also evolved in ways characteristic of larger (>100,000 m^2 or 10 Ha) islands, with 13 of the 16 islands either remaining stable or significantly increasing in area. We therefore highlight a potential need for an additional size threshold within Duvat's [11] small island category in which to examine island evolution. For example, in Cayos Cochinos, only islands <1500 m^2 experienced marked island change, whereas those >5000 m^2 remained stable (Table 4).

4.3. Timescales and Island Equilibrium

The sub-decadal accretionary (Utila) and erosive (Cayos Cochinos) trends observed may not be representative of longer-term island behaviour. Typically, reef islands exist in states of dynamic equilibrium with their surrounding environment, [1,72–74]. However, over decadal timescales, changes to this long-term equilibrium state, and island morphology, can be masked by shorter-term, but greater magnitude, shoreline changes; for example, those driven by periodic high-energy events [21,24,25]. Thus, reef islands are often identified as highly dynamic over months and years, but rarely as experiencing significant planform change over decades or centuries [11,27,66,71]. If Caribbean reef islands exist in similar states, it is likely that our data represents higher rates and magnitudes of sub-decadal shoreline change as opposed to the overall, long-term status of the islands. This point is highlighted where the inclusion of additional 2016 data for C1, C2, and C3 reverses the overall trends of island evolution from erosion between 2018 and 2021 to accretion between 2016 and 2021 (Table 4), and observation that the U4 spit was absent during a 2022 research visit, just 3 years after its presence in satellite imagery. Compared to previous studies that analyse island behaviour over multiple decades, these examples therefore highlight the highly dynamic nature of Caribbean islands over short, sub-decadal time periods, possibly within a longer-term state of dynamic equilibrium. Understanding reef island shoreline dynamics over such short timescales provides unique and important insights for decision makers in island management, particularly when designing reef island preservation strategies for eroding islands.

4.4. Drivers of Reef Island Evolution

As in the Pacific and Indian Oceans, the large diversity of shoreline change identified in this research likely reflects variability in geological, ecological and hydrodynamic processes, particularly mean wave and current regimes, between and within the study sites [18,39,68]. For example, the accretion and contraction of island spits and extremities, observed on 50% of all islands, could result from hydrodynamic regime-driven changes to longshore sediment transport [18,23,28,39,71].

As a key part of the Caribbean's hydrodynamic regime, high-energy events, namely hurricanes, are also likely to have contributed to the reef island evolution recorded in Utila and Cayos Cochinos. Such events have long been recognised as causing short-term, periodic and significant disturbances to reef island equilibrium and shorelines, as well as rapid island formation, including in nearby Belize [38,39,72,75]. During the period of this research (2006–2019), 13 tropical cyclones passed within 200 km of Utila, and 4 of Cayos Cochinos [76,77]. Although island behaviour cannot be attributed to specific events, the high-magnitudes of shoreline change observed across both sites over short periods (for example, 75% erosion of C8 between 2018 and 2021) is characteristic of reef islands in high-storm frequency settings (29, 97, 85, 93, 98). We also hypothesize that Storm Barry, which passed within 50 km of Utila in June 2013, was implicated in the erosion of all Utila cays between March and July of this same year—the only period in which all cays eroded (Table 2). Thus, we suggest that high-energy events may be a key driver of Caribbean reef island evolution.

As an overriding control of hydrodynamic regimes, we also anticipate that ongoing Caribbean sea-level rise throughout the study period [52] would have contributed to island evolution, specifically by inducing sediment reworking atop reef platforms [7,68,78]. However, any direct signals of sea-level rise in our data are likely masked by short-lived, higher magnitude shoreline changes, such as those caused by high-energy events.

Considering our focus on natural reef islands, it is unlikely that the observed shoreline changes were directly driven by anthropogenic disturbances. Indirectly, however, differences in population, tourism, and reef ecosystem management between tourist-hotspot Utila and the military patrolled Cayos Cochinos Marine Protected Area cannot be ruled out as impacting reef health, associated sediment production and thus island evolution. We suggest that further, local reef island monitoring is undertaken alongside research into the key, local drivers of reef island evolution. Such data would help direct future island management efforts towards any environmental, ecological, or anthropogenic drivers of erosive reef island behaviour.

4.5. Implications and Considerations

As one of the first studies of Caribbean reef island evolution, our results have implications for research considering reef island futures throughout the Caribbean and globally. Duvat [11] proposed a 'global trend' in atoll reef island stability and persistence based on data from the Pacific and Indian Oceans. While this trend is supported by our data, where the majority of cays either accreted or remained stable, it is contradicted by the substantial erosion of C1, C8, C9 and U7. Similarly, the majority of the Sapodilla Cays, Belize eroded between 1960 and 2012 [38,39], and more recently the Gardi Sugdub reef island communities in Panama been evacuated due to 'island sinking' [79]—all of which challenge the 'global trend' of stability. Thus, while the predominance of island stability and accretion in this research provides some optimism for reef island future physical stability, the above examples of marked erosion highlight a degree of Caribbean reef island vulnerability that may be problematic for reef island communities relying on the islands in their current states.

Data from Cayos Cochinos (where islands < 1500 m^2 experienced marked island change and those >5000 m^2 remained stable), also highlights the need for specific consideration of smaller (<1500 m^2) reef islands that may be more vulnerable to future climatic and environmental change than their larger counterparts. The dynamic nature of reef islands over the sub-decadal period of this research does suggest that Caribbean reef islands have a degree of natural resilience to environmental change. However, for the smaller, eroding islands, such as C8, additional coastal management may help prevent the remains of these islands disappearing completely. Any management should, however, work synergistically with, and not limit, the islands' natural dynamic behaviour and/or exacerbate erosion [24,54,80,81].

Our study also has implications for reef island monitoring methods, as observing reef islands over sub-decadal timescales may challenge the validity of using the vegetation line as a proxy for island shorelines [27,59]. Verbal communication with the Cayos Cochinos Fundación suggested that shoreline erosion has caused the disappearance of palm trees throughout the archipelago, which over longer timescales would represent erosion in the digitized shorelines. However, over shorter timescales this erosion may be misrepresented as accretion if initial shoreline erosion causes the trees to lean outwards, giving the impression of an expanded canopy in satellite imagery. Longer-term shoreline change data—especially from before the satellite era, and periods of sea-level rise and/or Caribbean coral reef degradation—would facilitate a more comprehensive assessment of the equilibrium state of Caribbean reef islands through recent environmental change. The longer the observation period, the less likely that any high magnitude but short-lived changes to island shorelines will bias overall trends in island behaviour [1,24,25,72].

To comprehensively assess of reef island behaviour, we also propose that the non-vegetated parts of reef islands are monitored in addition to the vegetation line. Analysis of non-vegetated island shorelines from satellite imagery is typically impossible due to the low contrast between beach sediments and reef flat, and difficulty in accurately identifying the toe of the beach at different tidal stages [27,59]. However, these reef island beaches are just as, if not more, dynamic than the vegetated island cores [29,71,73,81,82]. Excluding non-vegetated areas thus prevents important island evolutionary behaviour from being documented. For example, the unvegetated Cayo Gallo (Cayos Cochinos) was excluded from analysis, despite local reports of its rapid erosion and 'disappearance', suggesting that monitoring this cay should be a priority. The Cayos Cochinos Fundación and Garifuna community have also reported changes in the morphology of C1 and C7 beaches at faster rates (e.g., monthly, seasonally) than can be identified in island vegetation change analyses [29,71,73,81].

The exclusion of beaches from the majority of reef island shoreline change analyses is particularly relevant where local communities live and are reliant on the non- or sparsely vegetated parts of reef islands, such as on Suc-Suc Cay (Utila) and Chachauate II (Cayos Cochinos). Considering the stabilising role of vegetation on reef islands, and thus likelihood that non-vegetated islands will be less stable in the face of environmental change, it seems pertinent that island beaches are also monitored. The toe-of-beach and high-water marks could be informative, supplementary proxies for monitoring reef island change and detecting shorter-term island changes not expressed by the vegetation line [71,83]. Measuring these proxies could become more feasible with advancements in drone and fluid lensing technologies [84], or with local in-field efforts to collect this data using GPS. Indeed, regular local reef island monitoring would help develop a robust local knowledge base of the magnitude and key drivers of future Caribbean reef island evolution over a range of timescales, and inform reef island vulnerability assessments and adaptation strategies.

Finally, to comprehensively consider reef island evolution, we acknowledge the need for data regarding the 3D nature, and specifically the vertical dimension, of reef islands—something currently not readily available for these environments. This research emphasises the highly dynamic nature of reef islands in the Caribbean during a period of coral reef degradation and sea-level rise. However, evidence of reef island stability and accretion is not always synonymous with future island resilience, particularly regarding sea-level change. Lateral reef island evolution (examined here) provides important insights into reef island adaptive responses to environmental change in the planar dimension. Yet, this data will be of little relevance where sea level is predicted to rise above the low elevations typical of reef islands [41]. Additional data considering vertical reef island evolution will thus be key to assessing future reef island resilience.

5. Conclusions

This research presents the first analysis of reef island shoreline change from the Caribbean using DSAS methodologies and begins to address the Caribbean geographical gap in global reef island shoreline change databases. Our results reveal diverse reef island shoreline change behaviour between and within two neighbouring Honduran sites. In Utila, island accretion dominated between 2006 and 2019. Conversely, between 2018 and 2021 in Cayos Cochinos contrasting trends of reef island stability for islands >5000 m^2 and marked erosion and accretion for islands <1500 m^2 lead us to propose a new size threshold for considering reef island evolution. We also suggest that Caribbean reef islands may be smaller than their Indian and Pacific Ocean counterparts and are thus potentially more vulnerable to future environmental change and erosion. The range of modes of reef island change exhibited across all islands highlights—more than ever—the highly dynamic and heterogenous nature of reef islands over sub-decadal timescales, and periods coincident with sea-level rise. Thus, despite widespread negative views of island loss, we emphasise that reef islands (particularly those >5000 m^2) appear to have a degree of natural physical resilience to environmental change that should be acknowledged in any reef island management discussions. Future research focussing on longer timescales relevant to reef island equilibrium and vertical (3D) change will provide a more comprehensive understanding of reef island evolution. However, here we show the opportunity that high-resolution satellite imagery provides for conducting high-frequency assessments of reef island shoreline change over short periods (maximum 12.4 years) that are highly relevant for considering reef island futures in the face of environmental change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15194787/s1, Table S1. Satellite georeferencing error, human error (calculated as specified in Methods), pixel size and overall Root Mean Square Error (RMSE) for each shoreline for Utila and Cayos Cochinos reef islands.

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Data Availability Statement: The data presented in this study are available in this article and in Supplementary Table S1.

Conflicts of Interest: The authors declare no conflict of interest. The funders (NERC) had no role in the design, execution, interpretation, or writing of the study.

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