Short-term morphological response of rubble coral islands to the impact of a small tropical cyclone

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ABSTRACT

Tropical cyclones (TCs) are extreme storm events with the potential to cause significant damage to coral reef and island ecosystems. The evolution of coral rubble (shingle) islands within these ecosystems relies on the complex eco-morphodynamic relationship between the supply of biogenic sediment from the reef and subsequent transport by hydrodynamic forces. Storms have the potential to alter this relationship, posing a potential threat to rubble islands structure and stability with the forecasted increase of the intensity of storms in the Southwest Pacific with climate change. Traditional methods of monitoring the impacts of storm focus on long-term effects, often utilising field-based approaches. Here we use unpiloted aerial vehicles (UAVs) and remotely sensed data as a cost-effective method to provide high-resolution spatial data to understand short-term effects of tropical cyclones, and the resulting storm generated waves. We observed the impacts of TC Gabrielle (2023) on One Tree Reef within the Southern Great Barrier Reef and quantified the changes of One Tree Island (OTI), a well-developed rubble island (~5.9 Ha), and Two Tree Island (TTI), a developing rubble island (~0.1 Ha). At both islands, shoreline length decreased (-7.3% TTI, -0.5% OTI) and total rubble volume decreased (-1.8% TTI, -0.3% OTI). The rubble tracts attached to OTI prograded towards the island as result of the TC and distributed sediment along its shore. This study presents high-resolution data for remote rubble islands and incorporates a detailed volumetric analysis complementing traditional planimetric methods for the monitoring of remote islands.

KEYWORDS

Remote sensing; UAV; Tropical Storm; Climate Change; Sediment Transport; Geomorphic change.

Highlights

- Remote sensing provides a high-resolution data for measuring geomorphic change caused by tropical cyclones on coral reefs.
- Small islands are more vulnerable (six times) to erosion than larger islands.
- We present quantitative evidence of rubble transport occurring along rubble tracts.

1. INTRODUCTION

Coral rubble (shingle) islands are low-lying sedimentary features, typically <5 m metres above mean sea level (MSL) (Kench et al., 2015), which form on coral reef flats or infilled lagoons (East et al., 2018). Coral islands, both rubble and sand, provide Small Island Developing States (SIDS) with the only source of habitable land (Carruthers et al., 2023; Kench et al., 2015). For example, in the Southwest Pacific Ocean, SIDS such as Kiribati, Tuvalu and the Republic of the Marshall Islands; and in the Indian Ocean, the Maldives, are at the forefront of the climate emergency as result of the unpredictability of their response to increased wave exposure and risks of coastal erosion (Carruthers et al., 2023; Kench et al., 2015).

Coral rubble, which make up the majority of rubble islands, corresponds to calcareous sediments larger than sand derived from the organisms in the surrounding coral reef environments (Perry et al., 2011). The stability and evolution of coral rubble islands are controlled by complex eco-morphodynamic feedbacks between hydrodynamic forces (Kench et al., 2023; Talavera et al., 2021), the transport of carbonate sediments formerly produced by calcareous organisms at the forereef (rubble) (Perry et al., 2011; Tuck et al., 2021) (Tuck et al., 2021; Perry et al., 2011) and the availability of such sediments (Bryson et al., 2016; Kayanne et al., 2016). Sediment production (i.e., mechanical breakage of reef organisms) and supply rates are controlled by wave, tides and currents in both modal and extreme conditions (Masselink et al., 2020; Perry et al., 2011; Tuck et al., 2021). Large powerful storm waves associated to TCs can cause significant erosion to the reef framework and transporting gravel, rubble and sand (Vila-Concejo & Kench, 2017). These forces can drive the production and supply of the carbonate sediment in the reef environment and are required to build and maintain coral islands, as well as influencing island morphology and evolution (Perry et al., 2011; Tuck et al., 2021). In coral reef environments, wave energy is primarily dissipated by the forereef and reef crest, reducing the wave heights on the reef flat (Perris et al., 2024). Previous studies have found that the maximum wave propagation which allows for the transport of sediments occur during high tide. Therefore, the high-water levels (e.g., tide and storm surge) that occur during tropical cyclones (TCs) enable large storm waves to propagate over the reef flats, causing sediment transport (Harris et al., 2015; Vila-Concejo & Kench, 2017).

Due to the high population densities found in SIDS across the Indo-Pacific and sensitivity to environmental changes, it is important to monitor coral rubble delivery rates and island changes at an event-scale (TCs) to inform management decisions in light of future projections (Kench et al., 2015; Murfitt et al., 2017; Talavera et al., 2021; Ainési et al., 2024). Remote sensing techniques are useful in monitoring geomorphological features of coral reef ecosystems, due to their identifiable features in aerial and satellite imagery (Talavera et al., 2021). UAVs have allowed for planimetric (2D) analysis of shoreline and area changes to islands, as well as volumetric estimates from high-resolution mosaics and Digital Elevation Models (DEMs) (Murfitt et al., 2017; Talavera et al., 2021).

The aim of this paper is to explore the response of two rubble coral islands in the southern Great Barrier Reef to the passage of a small TC, including the (1) quantification of the geomorphic change on the coral rubble islands triggered by storm waves; and (2) characterisation of the role of rubble tracts in facilitating sediment transport towards the islands. These findings will provide an improved understanding of the short-term impact of extreme weather events on coral reef islands and the processes which influence island vulnerability, while providing insights into monitoring approaches for the monitoring remote islands.

2. METHODS

2.1 Site description

This study focuses on two low-lying coral rubble islands: One Tree Island (OTI), a vegetated stable island (~5.9 Ha), and Two Tree Island (TTI), a small developing island (~0.1 Ha), located within the eastern margin of One Tree Reef (Figure 1). One Tree Reef is a platform reef located approximately 90 km off the eastern Australian coast and 20 km west of the shelf edge, among the reefs in the Capricorn-Bunker Group, southern Great Barrier Reef (GBR) (Marshall & Davies, 1982; Shannon et al., 2012) (Figure 1). It is an asymmetrical triangular shaped reef (5.5 km long x 3 km wide) surrounded by depths of up to 60 m (Shannon et al., 2012) (Figure 1). Tidal conditions are mixed-semidiurnal and mesotidal, with an average tidal range of 3 m (Vila-Concejo et al., 2014). The reef is exposed to moderate wave energy with an average significant wave height (Hs) of 1.7 m, mean wave period (T_z) of 5.8 s, wave power (P) of 42 kW/mm and a mean south-east wave direction (θ_m) with no notable change other than that influenced by storms such as TCs (Smith et al., 2023).

The two islands are primarily composed of rubble carbonate sediments (Talavera et al., 2021). The morphology and sediment delivery to the shores has been linked to high-energy wave events that transport rubble onto the reef flat and then to the islands via longshore sediment transport and wave overtopping (Shannon et al., 2012; Talavera et al., 2021). One Tree Reef is periodically exposed to TCs between November and March (Shannon et al., 2012). Recent remarkable TCs include TC Hamish (2009), Yasi (2011), Ita (2014), and Marcia (2015) (Talavera et al., 2021), and recently, TC Gabrielle in 2023, which is the focus of this research. These TCs typically have high wind speeds (> 34 kt) and above average Hs, being the storm wave threshold for the GBR defined by as Hs > 2.9 m (Smith et al., 2023). These conditions provide an opportunity for rubble production and deposition onto the reef flat, altering sedimentary features such as rubble spits/tracts and coral islands (Thornborough, 2012; Vila-Concejo & Kench, 2017).

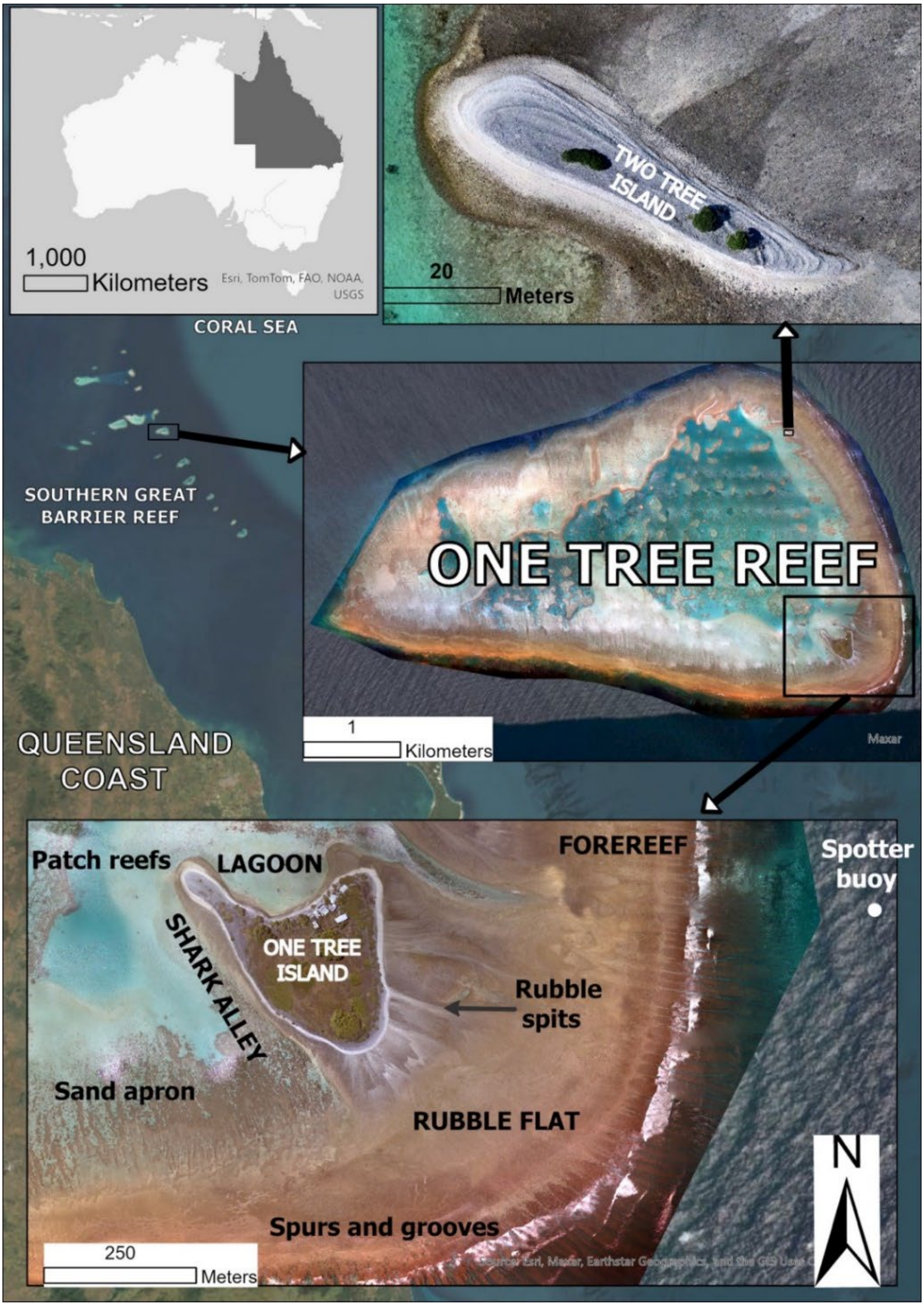

Figure 1. *Location of One Tree and Two Tree Islands within One Tree Reef, southern Great Barrier Reef, Australia* (Background image: ESRI, Maxar, Planet).

2.2 Local and Regional Waves and Tropical Cyclones

TC Gabrielle developed in the Coral Sea on the 5th of February 2023 south of the Solomon Islands (Bureau of Meteorology, 2023) (Figure 2). TC Gabrielle passed closest to One Tree Reef (510 km) on the 9th of February 2023 as a Category 1 cyclone (Saffir-Simpson Scale) and transitioned into a Category 2 cyclone before continuing moving southeast on the 10th of February 2023 and dissipating near Norfolk Island on the 12th of February 2023 (Figure 2).

We used two wave datasets for the study period from 22nd November 2022 to 1st of May 2023. The first was a Spotter wave buoy (Sofar Ocean inc.) located 400 m offshore from the reef crest to the east of One Tree Reef (Figure 1) in 16 m depth. Wave power (P) was calculated using linear wave theory, as

$$P = C_g E \qquad \text{Eq.1}$$

where, E is the wave energy density and C_g is the group speed determined for intermediate depths, such that:

$$C_g = \frac{c}{2}(1 + 2\frac{kh}{sinh2kh}) \qquad \text{Eq. 2}$$

where, c is the phase velocity, h is the water depth, and the wave number (k) and wave celerity (c) were derived using the Newton-Raphson method for the dispersion relation (Dean & Dalrymple, 1991).

For the second dataset, Hs, Tz, and P were obtained from regional satellite altimetry extracted using RADWave (Smith et al., 2023) for a 1 x 1 degree grid to the east of OTI (23–24°S, 153–154°E). Both wave datasets were compared to provide a comprehensive understanding of the offshore wave climate at One Tree Reef and identify changes in wave conditions during TC Gabrielle's movement along its track. Tide data was obtained from the 2023 Queensland tide table (Bureau of Meteorology, 2022) open data portal, with Gladstone tide gauge providing the closest data point to One Tree Reef (-23.50°, 151.15°).

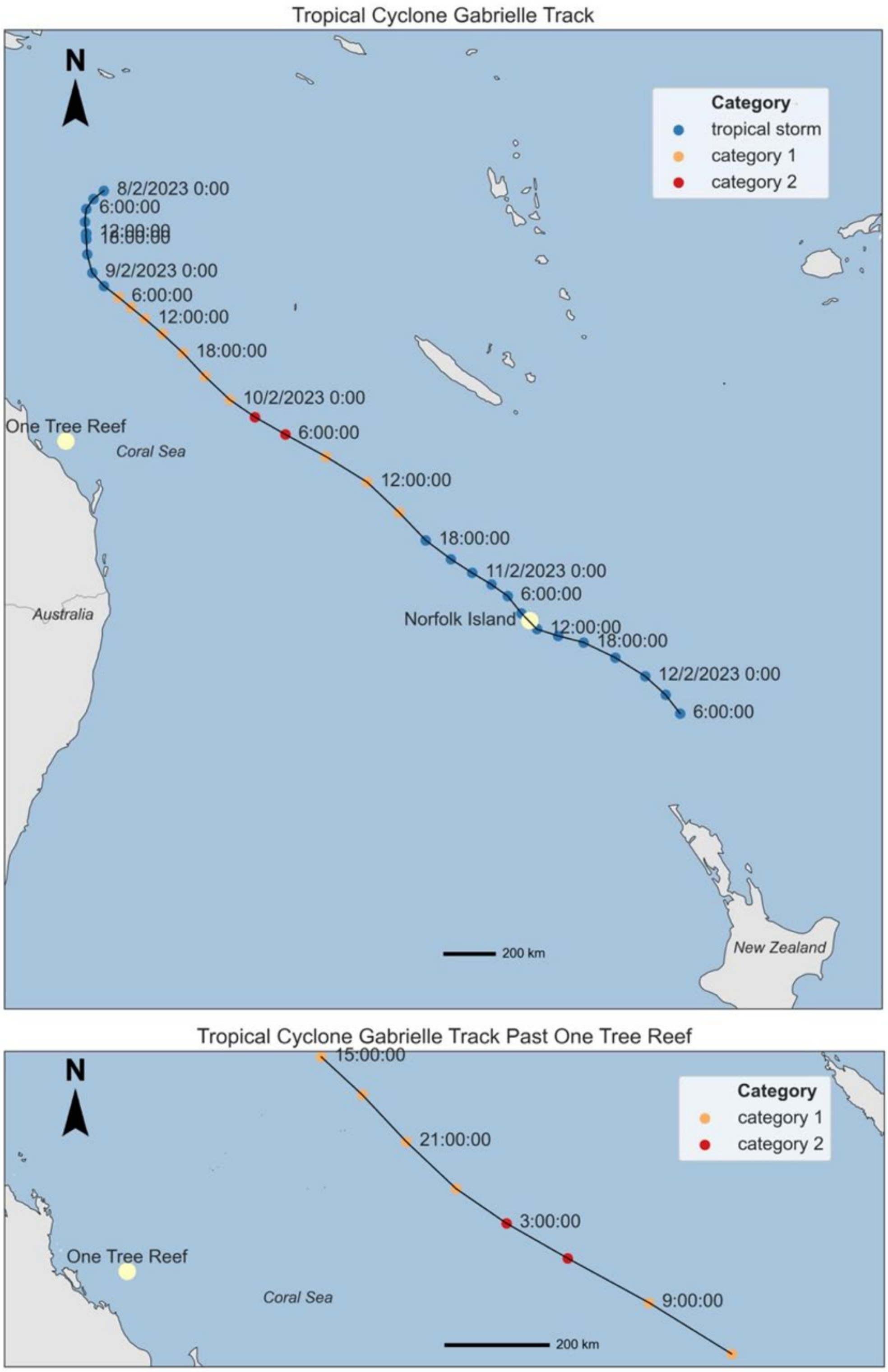

Figure 2. *Track of Tropical Cyclone Gabrielle (top) and track past One Tree Reef at the peak of the storm 9th Feb 15:00 to 10th Feb 12:00 (bottom) categorised according to the Saffir-Simpson Hurricane Wind Scale. TC Gabrielle's track is obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) dataset* (Knapp et al., 2010).

2.3 UAV and LiDAR Data

UAV surveys were conducted at both OTI and TTI on November 2022 and March 2023 using a DJI Phantom 4 RTK Drone with a 20 megapixel Red-Green-Blue camera (Table 1). Ground control points (GCPs) were placed across the flight paths areas and their location and elevation were recorded using a Real-Time Kinematic-Global Navigation Satellite System (RTK-GNSS) (Trimble R10) to later geo-reference the UAV images (Figure 3). The vertical and horizontal uncertainty for the RTK GCPs were ±0.05 and ±0.1 m, respectively. We also included additional control points, selected in reef areas that had experienced no change (e.g., notable boulders on the reef flat, edge of buildings) when compared to the 2018 LiDAR Digital Terrain Model (DTM) of One Tree Reef, where the vertical error of the point cloud was ±0.1 m (Harris et al., 2023). . The UAV data was processed using Agisoft Metashape (Version 2.1.1) to produce high-resolution photo orthomosaics and digital elevation models (DEMs). We used 7 Individual Checkpoints to assess the vertical accuracy of the November 2022 and March 2023 DEMs for both OTI and TTI, which displayed RMS errors of 0.11 and 0.12 m, and 0.11 and 0.12 m respectively. The mosaics and DEMs were imported into ArcGIS Pro (Version 3.2.2) for the planimetric (2D) and volumetric (3D) island analyses.

2.3.1 Island Morphometrics: Planimetric (2D) Analysis

The shoreline proxy used in this study was the stability line (also known as the beach toe), which has been shown by Duvat & Pillet (2017) to be suitable for mapping coral reef islands. The stability line is the outward limit of stabilised rubble deposits, reflected by the darker appearance of these reef areas (Duvat & Pillet, 2017). This proxy is useful for unvegetated islands lacking the edge of vegetation and has been used extensively (e.g Kench et al., 2015). Following Husband et al. (2023), the shoreline was manually digitised 10 times for each survey and island by the same user. To maximise the ability to digitise small scale changes, we used a scale of 1:250 for TTI, and 1:2,500 for OTI differing due to the size difference of the islands. Three sources of shoreline uncertainty were considered (Fletchert et al., 2003; M. Ford, 2012): image resolution (pixel size), georeferencing error and the human digitisation error. These were calculated for each timestamp and island using the Root Mean Square Error (RMSE) approach (Fletchert et al., 2003; M. Ford, 2012). The total horizontal uncertainty is this study ranged from ±0.60 m to ±0.99 m.

Using an averaged shoreline from the 10 repeated measures for each survey, the island area (A), perimeter length (P) and location (centroid coordinates) were quantified. The shape of the island, based on the digitised shoreline polygon, was determined by calculating circularity (0 to 1; 1 being a perfect circle) as:

$$C = \frac{4\pi A}{P^2} \qquad \text{Eq. 3}$$

where, A is the area of the island and P is perimeter.

Table 1. *Technical details of the UAV surveys conducted at One Tree Reef in November 2022 and March 2023.*

Date	Location	Mapped areas	Flight height (AHD)	Number of images	Pixel size (cm)	Front-side overlap	Camera angle	Number of GCPs
November 2022	One Tree Island	Shoreline North	55	201	1.51	80 - 80 %	-60°	43
		Shoreline Northwest Spit	55	238	1.51			
		Shoreline West	55	449	1.51			
		Shoreline Southeast	70	366	1.92			
		Shoreline East	55	306	1.51			
	Two Tree Island	Entire Island	70	583	1.92	80 - 80 %	-60°	7
March 2023	One Tree Island	Shoreline North	55	420	1.51	80 - 80 %	-60°	40
		Shoreline Northwest Spit	55	388	1.51			
		Shoreline West	55	604	1.51			
		Shoreline Southeast	70	430	1.92			
		Shoreline East	70	430	1.92			
	Two Tree Island	Entire Island	70	539	1.92	80 - 80 %	-60°	9

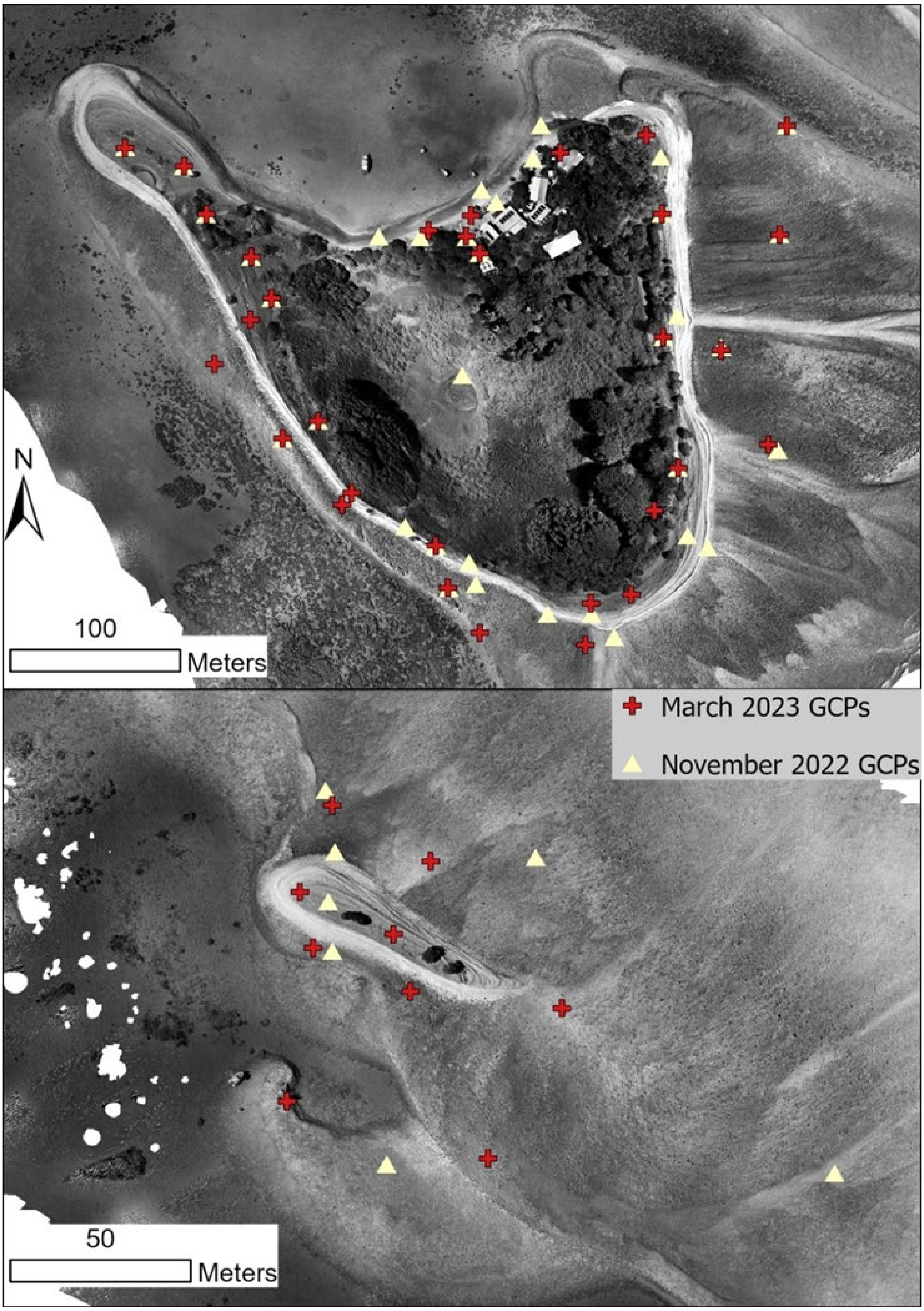

Figure 3. *Location of GCPs for November 2022 (yellow triangle) and March 2023 (red cross) at One Tree Island (top) and Two Tree Island (bottom). Background image: November 2022 orthomosaic.*

2.3.1 Island Morphometrics: Volumetric (3D) Analysis

To quantify the impact of the TC on the patterns of rubble erosion and accretion, DEM difference plots were obtained by subtracting the DEMs from November 2022 and March 2023, produced separately for each island. To improve the estimations of geomorphic change, the vertical errors of the DEMs (±0.16 in 2022 and ±0.16 m in 2023) were propagated as uncertainties in the computed difference plots (Wheaton et al., 2010). Changes in the DEMs associated with the propagated vertical uncertainty were excluded from the analysis.

The islands volumetric change for each timestamp were calculated using the corresponding DEM and each island base elevation, obtained using the islands contours, which were found to be 0.6 m above MSL for TTI and 0.9 m for OTI. The DEMs elevation is in the Australian Height Datum (AHD), which is comparable to mean sea level (MSL), and therefore the reference plane height was set to 0 m. Sections of rubble accretion and erosion found in the difference plots were extracted and the volume for each timestamp was calculated and compared.

3. RESULTS

3.1 Local and Regional Hydrodynamic Conditions

The local nearshore and regional offshore wave conditions measured during TC Gabrielle revealed an increase in the wave conditions compared to the average conditions from the whole study period (Figure 4, Table 2). Local wave conditions recorded at the nearshore wave buoy measured a 50% increase in the mean H_s (Figure 4a, Table 2) with a maximum height of 3.6 m, a 20% increase in the mean T_z (Figure 4b, Table 2) with a maximum of 10.7 s, a mean θ_m of 101.5° (East-Southeast). This resulted in a 140% increase in mean P (Figure 4c, Table 2) with a maximum of 142.5 kW/m.

The peak of the storm, when TC Gabrielle was passing the closest to One Tree Reef (Figure 2), coincided with high tide, allowing for maximum wave propagation towards the islands. During this time the local wave conditions had a mean H_s of 2.9 m with a maximum of 3.6 m (Figure 4a), a mean T_z of 6.4 s with a maximum of 7.4 s (figure 4b), a mean θ_m of 94.4° (East) (Figure 4c) and a mean P of 62.6 kW/m with a maximum of 103.5 kW/m (Figure 4d). The waves shifted from their usual east southeast (θ_m 103.2°) to east northeast (00:00 10 Feb; θ_m 76.2°) at the peak of the high tide (3.54 m) during the transition from Category 1 to 2. The wave directions then switched back to ESE (~02:45 10 Feb; θ_m ~ 108°) as the tide began to drop, which was when the maximum H_s, T_z and P occurred and when TC Gabrielle fully reached Category 2. Lastly the waves switched back to east northeast (04:00 10 Feb; θ_m 80°) as the tide was low (~1.8 m).

During our study period, there were other periods when the H_s and *P* was above the storm threshold (Hs > 2.9 m) aside from TC Gabrielle (Figure 4). The most notable being Tropical Storm Hale, forming 31st December

2022 and dissipating 4th of January 2023 (mean H_s 2.0 m, T_z 6.9 s, P 33.4 kW/m and θ_m 108°). This storm had a rapid and distant passage from One Tree Reef, causing minimum impact in comparison to TC Gabrielle (Figure 4). Overall, TC Gabrielle has driven the largest waves at One Tree Reef, due to its closer storm track and larger storm magnitude in comparison to other events occurring during the study period, with a mean power almost twice as much as the second largest event, Tropical Storm Hale.

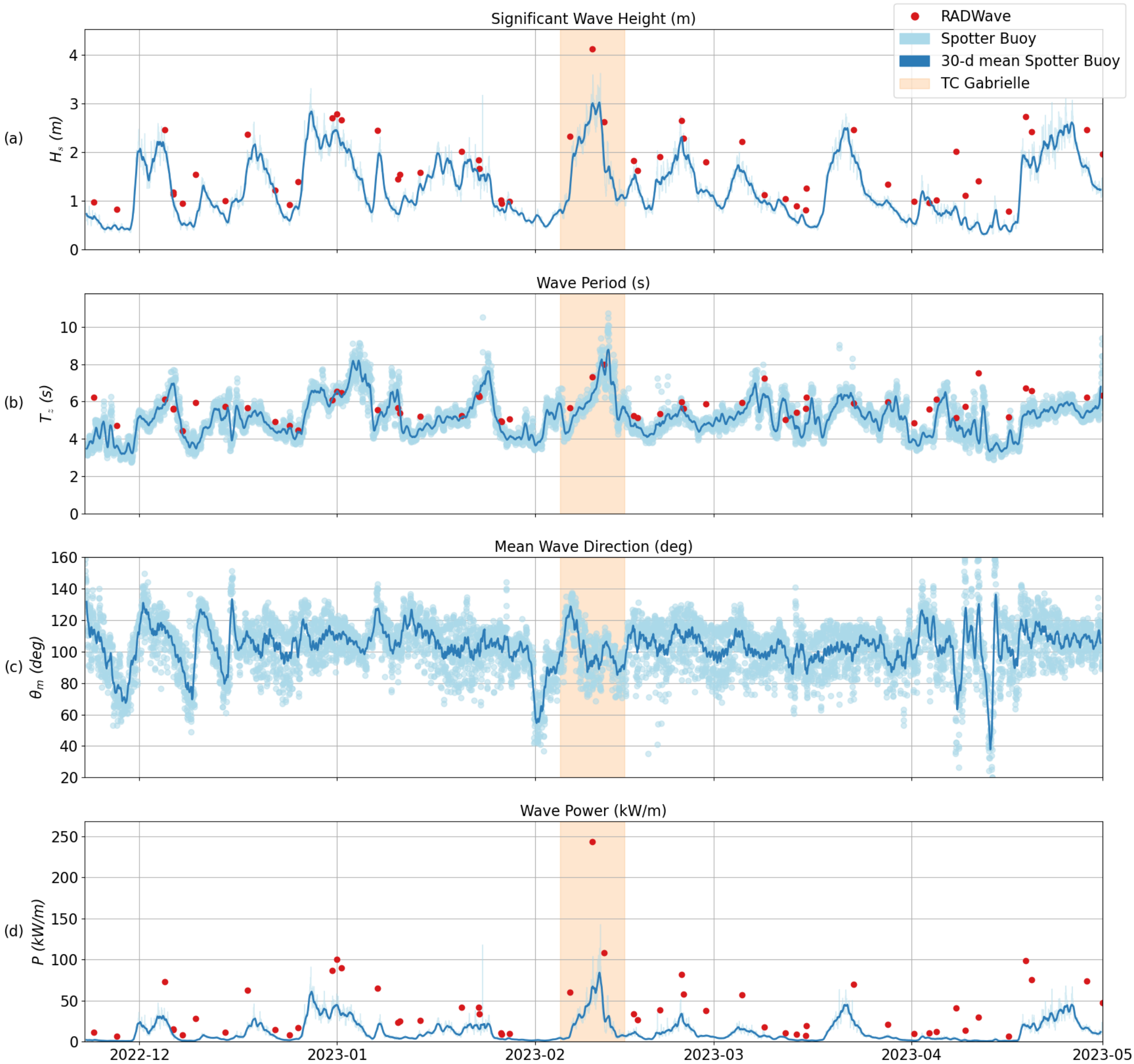

Figure 4. *Hydrodynamic conditions at One Tree Reef during the study period (22/11/2022-01/05/2023) with the TC Gabrielle event highlighted: (**a**) H_s (m), (**b**) T_z (s), (**c**) θ_m (deg), and (**d**) P (kW/m).*

Table 2. Mean wave conditions at One Tree Reef during the entire study period and during TC Gabrielle

Parameter	Hs (m)		Tz (s)		θ_m (°)		P (kW/m)	
Time	**Study Period**	**TC Gabrielle**	**Study Period**	**TC Gabrielle**	**Study Period**	**TC Gabrielle**	**Study Period**	**TC Gabrielle**
Location								
Nearshore	1.2	1.8	5.1	6.1	103.2	101.5	12.1	29.0
Offshore	1.6	3.0	5.6	6.9	n/a	n/a	38.3	137.1

3.2 Two Tree Island Geomorphic Change

Two Tree Island (TTI) became slightly more circular post TC Gabrielle (0.48 to 0.56 in circularity) (Table 3) due to the erosion of the perimeter of the southeastern spit (Figure 5a) which caused a slight northwest centroid shift of 0.56 m (Figure 5a). Adjacent to this, on the northeast side of the island we observed accretion with a 3.8 m change in the shoreline position seaward (Figure 5a). Overall, the shoreline perimeter retreated by 13.3 m, while the area of the island slightly increased by 0.7% likely related to the change in circularity (Table 3).

The southeast spit experienced a net rubble volume loss of 39.6 m^3 (1.8 % loss), with vertical erosion values ranging from 0.17 to 0.8 m (Table 3). The sediment lost was mainly re-distributed towards the northeast island shoreline, contributing to accretion of 36.5 m^3 (vertical accretion ranging from 0.17 to 0.6) (Figure 5b). Slight accretion was also observed west to the southeast spit (3.6 m^3) (Figure 5b). Additional rubble loss was observed along the southwest shoreline (18.1 m^3) and the northwest tip (5.3 m^3) (Figure 5b). Adjacent to the erosion at the northwest tip, slight accretion was observed (3.2 m^3) (Figure 5b).

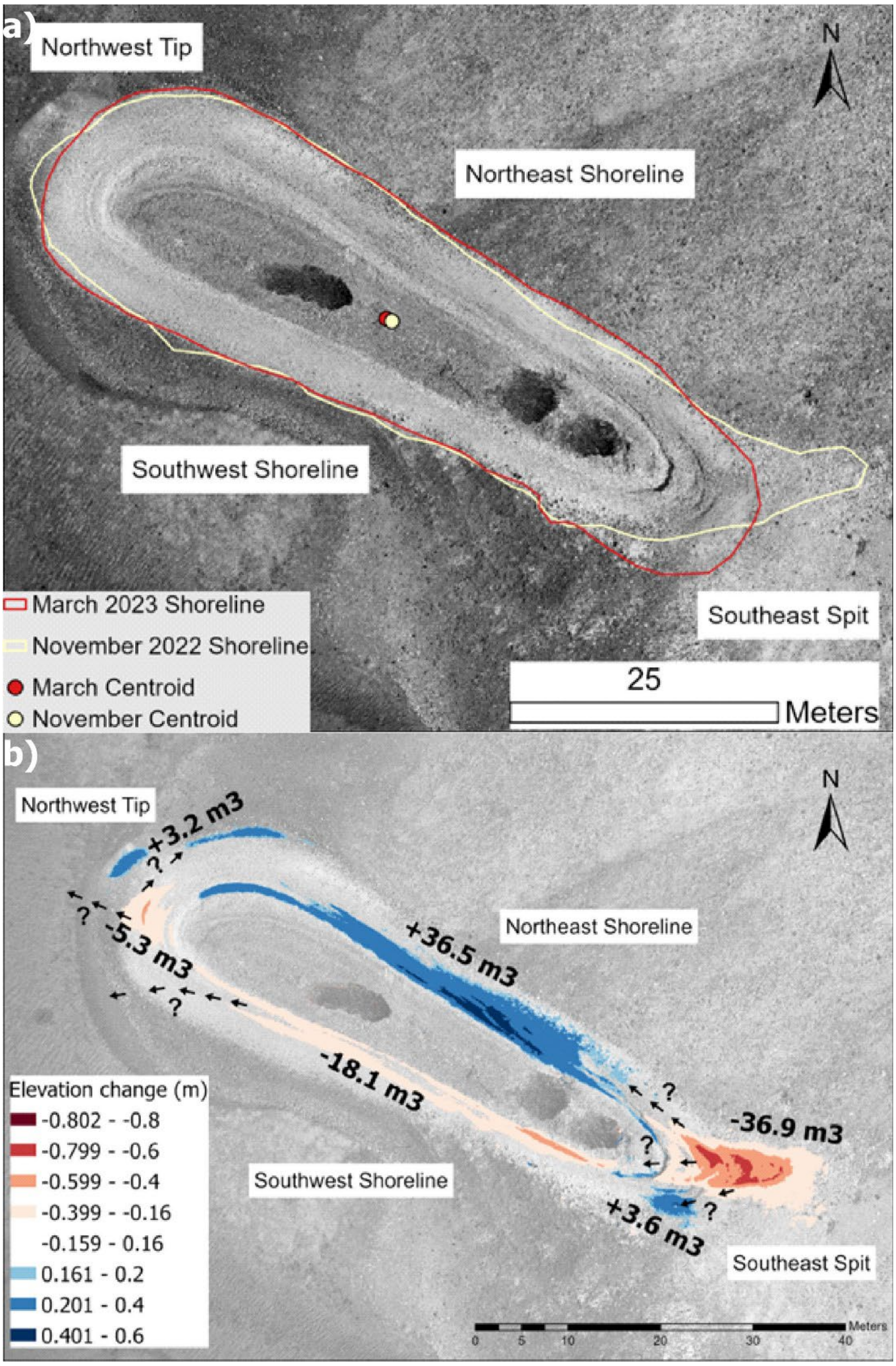

Figure 5. a) *Shoreline and centroid changes at TTI November 2022 (yellow) to March 2023 (red). Background image: March 2023 UAV orthomosaic.* ***b)*** *DEM difference plot of Two Tree Island from November 2022 to March 2023. Warm colours (reds) denote elevation loss (erosion) and cool colours (blues) denotes elevation gain (accretion). Arrows indicate the potential direction of sediment movement based on TCs Gabrielle's wave direction and power.*

Table 3. Geomorphic analyses of Two Tree Island and One Tree Island pre (November 2022) and post (March 2023) Tropical Cyclone Gabrielle.

		Two Tree Island			One Tree Island		
	Parameter	**November 2022**	**March 2023**	**% Change**	**November 2022**	**March 2023**	**% Change**
Planimetric (2D) analysis	Circularity (0-1)	0.48	0.56	+0.1	0.52	0.53	+1.9
	Area (m^2)	1,286.1	1,295.6	+0.7	59,264.6	58,985.3	-0.5
	Perimeter (m)	183.4	170.1	-7.3	1,226.6	1,202.7	-2.0
	Centroid Shift	0.56m east southeast			0.45m northeast		
Volumetric (3D) analysis	Volume (m^3)	2,200.7	2,161.1	-1.8	209,288.4	208,716.3	-0.3

3.3 One Tree Island Geomorphic Change

The change in circularity of One Tree Island (OTI) was negligible (0.52 to 0.53) (Table 3). There was a slight shift in the centroid location in north-east direction by 0.45 m (Figure 7; Table 3). However, the shoreline position of OTI was altered post TC Gabrielle. Overall, OTI shoreline perimeter retreated by 23.9 m and its area decreased by 279.3 m^2 (Table 3). At the north-west spit, it was observed a shoreline retreat of 1.8 m, while the opposing east shoreline accreted 2.1 m (Figure 7b). The accretion of the shoreline to the east of the northwest spit was observed across the lagoonward shoreline with accretion ranging from 0.4 to 1.8 m. At the northeast spit of the shoreline, about 0.5 to 1 m of erosion was observed (Figure 7e). The northeast spit also experienced erosion of 3.4 m with accretion occurring directly south by 1.6 m (Figure 7e).

Approximately 3.7 m of shoreline retreat was measured for the eastern shoreline, where the rubble tract joined the island. Directly south of this point, however, it was measured approximately 2 m of shoreline progradation (Figure 7d). Further, we found at the southeast shoreline retreated ranging from 1 to 2.2 m, with most of the erosion occurring at the junction with a rubble tract. Accretion was measured moving south towards the southernmost edge of the island with about 2.4 m of shoreline progradation (Figure 7c).

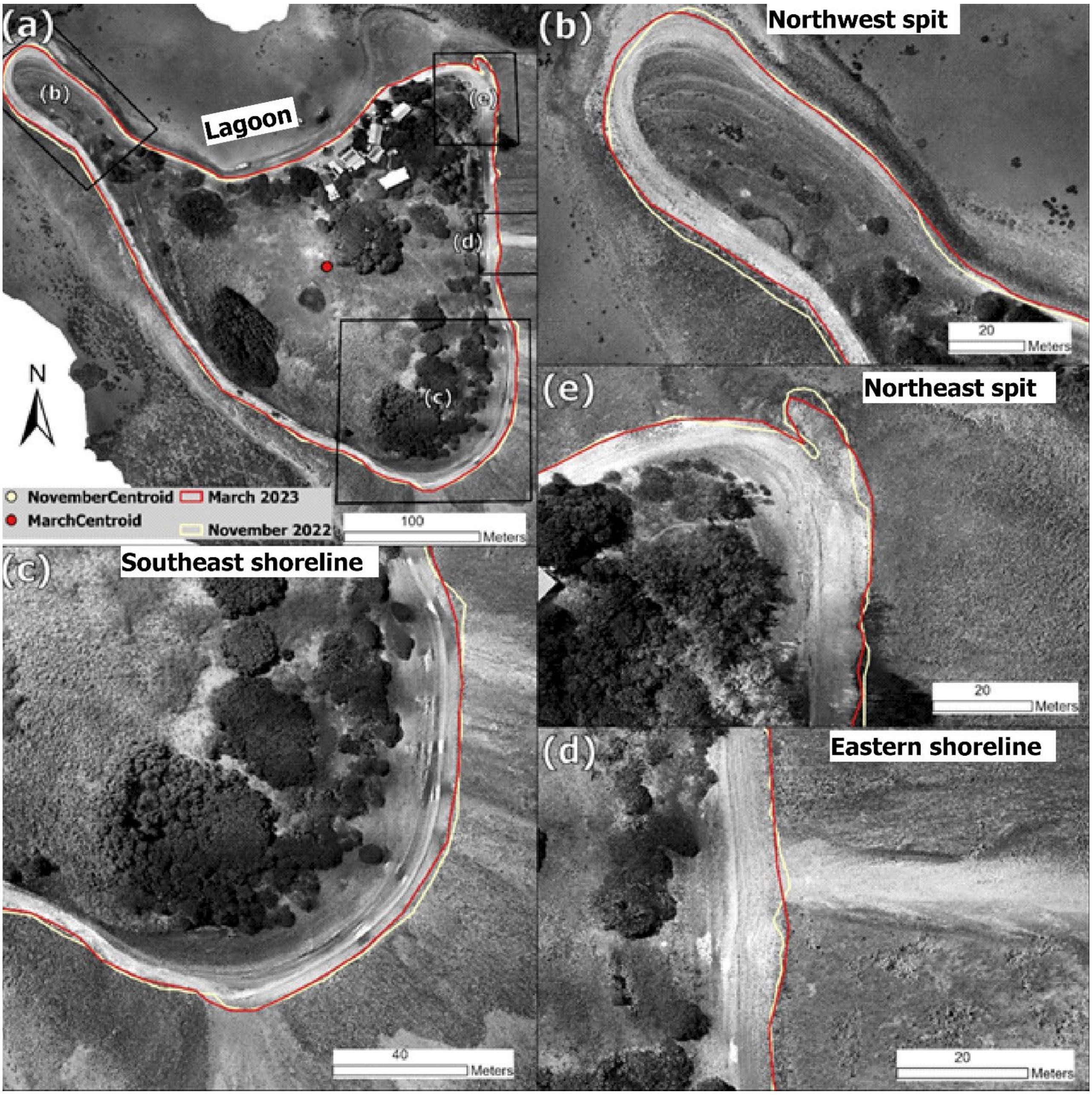

Figure 7. *(a) Shoreline and centroid changes at OTI from November 2022 (yellow) to March 2023 (red) (b) Northwest Spit (c) Southeast shoreline (d) Eastern shoreline at the rubble tract (e) Northeast spit. Background image: 2023 UAV orthomosaic.*

The total volume of OTI decreased by 572.1 m^3 (0.3 % loss). We observed an anticlockwise rotation at the northwest spit (Figure 8a), with the lagoon-side of the spit being vertically eroded from 0.17 to 0.63 m AHD (-42 m^3) (Figure 9b). Vertical accretion was observed on either side of this erosive spot (Figure 9b), with rubble volume increase of +21.8 m^3 to the southwestern side and +15 m^3 on the lagoon side (Figure 9b). Vertical accretion on both sides was of about 0.25 - 0.45 m.

Rubble deposits on the eastern reef flat showed relative rubble movement towards the island as result of TC Gabrielle (Figure 5, 9d). We measured a loss of 3.1 m^3 on the rubble tract at 45 m offshore, followed by a shoreward gain of 2.6 m^3 (Figure 8d). This change represents a 16.6 m of rubble transport towards the island. Vertical erosion is evident (from 0.17 m to 0.29 m AHD) at the rubble tract connection to the island, with a volume loss of -23.1 m^3 (Figure 8d). Immediately shoreward, it was observed vertical accretion (0.17 m to 0.32 m) with about +4.4 m^3 of rubble volume gained (Figure 8d). Continuing to the southeast of the island, there was significant erosion on the eastern side (-183.1 m^3) with adjacent vertical accretion and rubble gain at the southernmost part of the island (ranging from 0.19 to 0.75 m; +11.2 m^3) (Figure 8c).

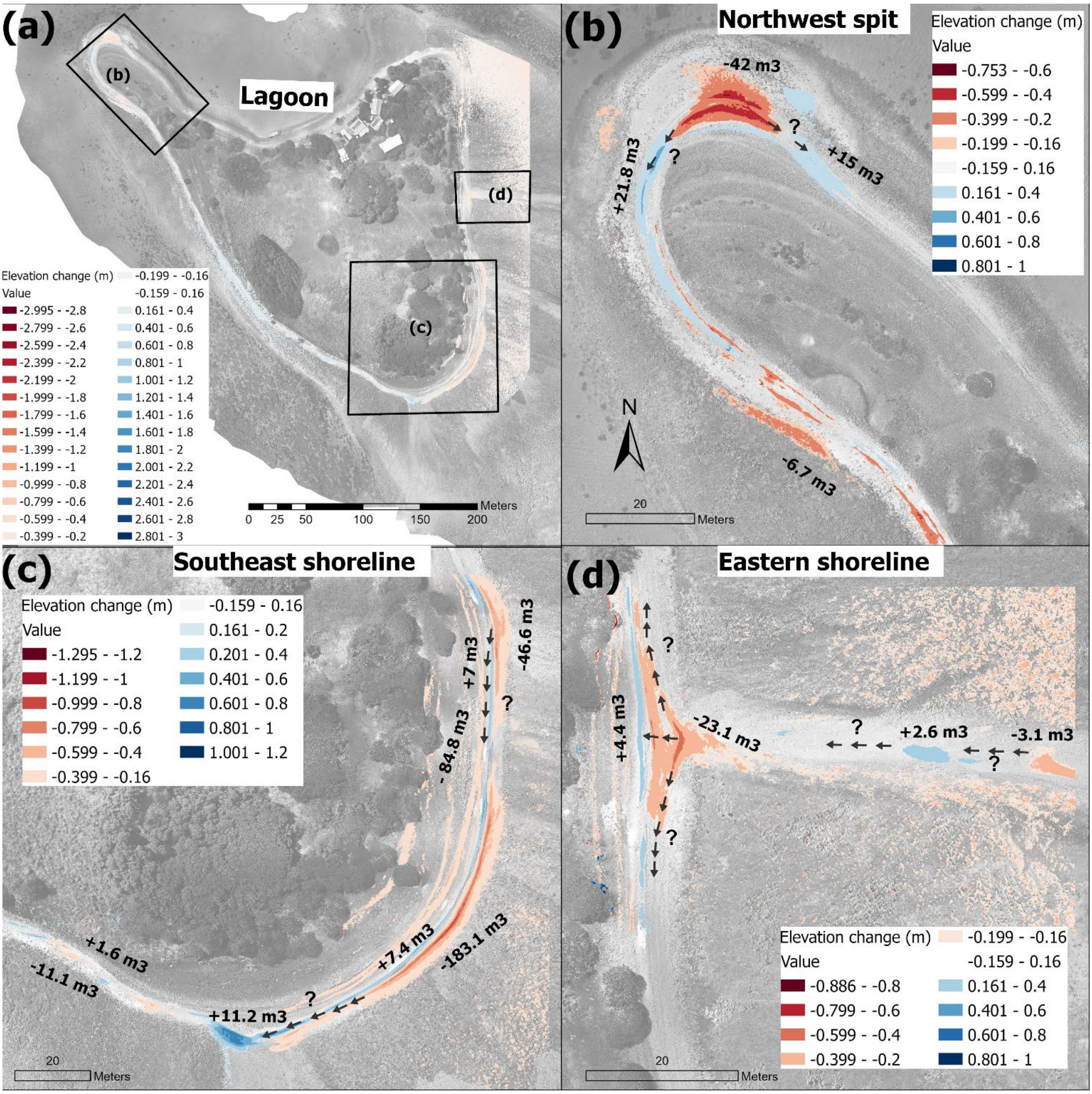

Figure 8. *DEM difference plot at One Tree Island from November 2022 to March 2023. Red indicates elevation decrease (rubble loss) and blue indicates elevation increase (rubble accretion). Arrows indicate the probable direction of sediment movement. (a) Entire OTI, (b) Northwest spit, (c) Southeast shoreline and (d) Eastern shoreline at the rubble tract*

4. DISCUSSION

4.1 Rubble transport on rubble tracts.

Our results show that TC waves during high tide transported coral rubble along rubble tracts, located on the reef flat, towards the island shores. Our novel dataset including high-resolution surveys pre- and post-storm on remote rubble detected a TC driven landward migration of rubble of approximately 16 m (Figure 9d). This is supported by the mode of rubble transport occurring at OTI suggested in Talavera et al., (2021), where rubble tracts act as conduits for sediment transport, delivering rubble to the island. These transport patterns also are also aligned with the earlier works of Maragos et al., (1973) that observed the formation of a rubble tract following TC Bebe (1972) acting as the shoreward migration of storm-deposited rubble and boulders from the reef edge to the island in Tuvalu. Sediment tracer studies in the Ryukyu Islands, Japan quantified rubble transport across the reef flat and towards the island during storm conditions (Iguchi & Hongo, 2018). Our results show that a small TC but with enough wave energy, such as TC Gabrielle, is capable of triggering rapid rubble transport towards the island.

Our findings represent a step forward in understanding the link between the reef flat, rubble tracts, rubble islands and storm events in supporting the evolution of island features in response to high wave energy. Studies in Tuvalu after TC Bebe in 1972 (Baines & McLean, 1976) show that a series of subsequent storms was necessary to move the fresh storm-generated rubble from the reef flat onto the shore along these newly formed tracts ultimately leading to island accretion. Meanwhile, similar trends were described in the Pacific (Kench et al., 2017), finding that rubble deposited onto the beach face after a high energy event can remain unmoved for several months. Recent research has focused on rubble delivery from cyclones and also on rubble movement along tracts in the Maldives (Gea-Neuhaus et al., 2025). Moreover it has been established that rubble can be delivered to the reef flat though the grooves in the forereef (Vila-Concejo et al., 2025), this was observed along the entire eastern margin of One Tree Reef. However, it is important to point out that while rubble tracts play a crucial role delivering rubble to OTI, there are no clearly defined rubble tracts at TTI. This emphasises the need to continue monitoring the short-term volumetric and geomorphic changes to complement long-term planimetric studies in the face of climate change.

4.2 Geomorphic change on rubble islands caused by small tropical cyclone

As Tropical Cyclone (TC) Gabrielle passed near the study site, the reef received waves from an atypical direction (east-northeast) with maximum wave power at 6 times the regional mean (38.3 kW/m) and 12 times the local mean (12.1 kW/m) (Figure 4). These wave conditions triggered notable geomorphic changes at both islands. The influence of TCs on island geomorphology is a documented process in the literature (Hongo et al., 2018; Scoffin, 1993; Vila-Concejo & Kench, 2017). Predicted increases in the intensity and frequency of TCs under further climate change scenarios (Fellowes et al., 2022; Hongo et al., 2018; Kench et al., 2015; Masselink et al., 2020; Sengupta et al., 2023), highlight the urgent need to better understand their short-term impact to coral reef environments and island morphology.

Using the high-resolution difference plots, we find that as result of the wave climate during storm event the rubble was redistributed around the island shores. For example, the northwest island spit at OTI experienced sediment accumulation to the southwest of the spit in line with the east-northeast TC waves (Figure 5; 9b). Meanwhile, the north-west movement of sediment from south-east tip of TTI was evident with the east-southeast TC waves (Figure 6; 7). Decadal (long-term) shoreline studies of OTI (Talavera et al., 2021) suggest that this type of sediment transport or rotation of the shoreline on the north-west spit can occur as a result of north-northeast wave directions. Further, due to the high tide at the peak of the TC (3.54 m), we observe rubble accretion at the shore in an area that extends towards the southeast of OTI (Figure 9c & 9d), possibly resulting from longshore transport during the high tide. The effect of wave direction on sediment transport and coral island shoreline change has highlighted the different transport processes between wave conditions and sand transport compared to storm conditions and rubble transport to island shores (Kench et al., 2017; Mandlier & Kench, 2012), with authors linking sediment transport to the wave conditions (Ortiz & Ashton, 2019). We observed that the atypical east northeast wave direction of TC Gabrielle resulted in a slight shift in both island centroids (Figures 6 and 8), highlighting that the location of island centroid coordinates are dynamic and can shift in response to changes in wave direction (Kennedy, 2024). Remarkably, our results show that the magnitude of the centroid shift is the largest for the developing island, TTI, demonstrating their increased vulnerability to the impacts of climate change (Fellowes et al., 2024).

Both island shoreline lengths decreased during TC Gabrielle (by 23.9 m and 13.3 m, respectively) in response to the storm waves. The observed patterns of accretion and depletion around both islands suggest that the sediment deposits are being pushed onshore and alongshore (Fig 9). Further, the total area of OTI decreased by 279.3 m^2 (-0.5%) while TTI increased by 9.5 m^2 (+0.7%), indicating a difference in response likely due to the size and stability difference between these islands. The change in shoreline and area is consistent with previous studies investigating changes overtime and also attribute stability as a factor of change. (Ford & Kench, 2015; Kench et al., 2018; Talavera et al., 2021; Webb & Kench, 2010). For example, Webb and Kench

(2010) showed that 43% of 26 atoll island surveyed in the Pacific have stable areas (<3% area changes), while 43% are accreting (growing) and 14% shrinking (eroding). More studies on short-term post-storm impacts on stable islands like OTI and less stable islands like TTI which include planimetric and volumetric changes would improve our understanding of the response of different island settings to storms. While acquiring the necessary dataset to reproduce our study in other locations is challenging, the knowledge of immediate island response to storm events (even small ones such as TC Gabrielle) is vital for management of coral island livelihoods and prediction of changes under future climate and sea level rise scenarios.

A small decrease in volume was found at both islands following TC Gabrielle, with -0.3% at OTI and -1.8% at TTI (Table 2). Volume change following extreme storm events has previously been documented, for example Talavera et al. (2021) noted the impacts of Tropical Cyclone Hamish, attributing this event as a major factor responsible for the geomorphic change found over a period of six years. Further, Spiske et al. (2022) looked at the impacts of Hurricane Irma on a low-lying tropical island finding an initial erosion of large volumes of sand at surveyed sites post-storm with sediment found to be washed into the nearshore waters. The volume of sediment loss which occurred at the beach toe (shoreline) on the southeast side of OTI (Figure 8c) exposed to the east-northeast storm waves reflects these findings as following TC Gabrielle sediment may have been redistributed onto the reef flat adjacent to the island attributing to the total loss of volume experienced. We provide accurate data on the short-term, high-resolution response of both a developed (OTI) and developing island (TTI) to the same event. We demonstrate that even small TCs can have outstanding effects on coral rubble islands. Recording these varying responses is vital for assessing island resilience and vulnerability. By examining how islands with different development levels react to identical extreme weather conditions offers valuable insights that can guide future adaptation strategies.

The volumetric changes to the island shoreface due to the TC waves present complex responses that are not observable with planimetric analysis. At both OTI and TTI, we found erosion at the base of the shoreline (e.g., at the rubble tract on the eastern exposed shoreline of OTI and at the southeast spit at TTI) followed by subsequent accretion on the upper shoreline area, patterns which may indicate wave-driven overtopping potentially as result of the hydrodynamic environment during the cyclone (Figure 5; 7; 9). Overtopping is an important process in sandy coral islands (Masselink et al., 2020) and it is suggested to be one of the drivers of coral rubble movement to shores (Talavera et al., 2021). We interpret that the rubble is being transported via wave-driven longshore transport to other areas of the islands after overtopping has occurred. This is seen from the rubble that accreted on the shoreline continuing to accrete moving in a southward direction, accumulating at the southernmost tip (Figure 9c; 9d). Earlier research (Kench et al., 2017) observed that storm deposited rubble on the beach face can remain unmoved for months or years; yet our study shows an almost immediate redistribution even with a small cyclone. The pattern of rubble loss and gain around the islands provides insights into how cyclones induce mechanisms of island growth and evolution. The use of simple, cost effective yet high-resolution UAV data to quantify the short-term volumetric geomorphic changes to rubble islands post TCs is an excellent tool for better understanding rubble transport mechanisms.

5. CONCLUSION

Our study allows for detailed insights into the short-term impacts of tropical cyclones on coral rubble islands. The use of remote sensing and UAV combined with local hydrodynamic measurements provides valuable high-resolution data that allowed an improved understanding of the morphological response of two coral rubble islands on One Tree Reef in the southern Great Barrier Reef to the passing of a small tropical cyclone.

Despite TC Gabrielle being a relatively small TC, our results demonstrate that the event was enough to trigger a geomorphic response at both islands, resulting in planimetric and volumetric changes. The combination of high tide, waves larger than usual, and a change in wave direction occurring at the peak of the TC were key hydrodynamic factors triggering the islands' eco-geomorphic response. Both islands experienced a change in size (OTI -23.9 m; TTI -13.3 m), area (OTI -279.3 m^2; TTI +9.5 m^2) and volume (OTI -572.1 m^3; TTI -39.6 m^3). This reflects the importance of understanding the hydrodynamic environment as a driver of sediment transport, with tide, storm wave direction and wave power crucial factors of morphological impact and the distribution of sediment. We demonstrate that rubble transport on the reef flat is essential to deliver sediment to the islands, with rubble tracts, on the large, developed island reef flat, acting as critical features to facilitate sediment transport to the island shore. While rubble tracts appear to be a vital in island sediment transport, there is limited research available about their formation and role in island development.

We observed that OTI, a stable, vegetated island suffered less impact on their overall position compared to a less stable, incipient islands like TTI. This raises questions about what factors are involved in ensuring islands stability overtime and presents uncertainty for incipient island resilience. Given that it is assumed that every island begins as an incipient one, it is essential to understand how to facilitate island growth and understand the influences to island geomorphological change with the increased threats of climate change.

Short-term monitoring of islands is critical in understanding storm impacts, especially in smaller developing islands such as TTI which elicited a greater response at an event scale compared to OTI, the stable, vegetated island. Future studies should quantify the tipping points at which unstable islands might become stable under given circumstances. It remains essential to explore innovative methods for monitoring rubble transport and subsequent island changes enabling effective management and protection of coral reef ecosystems.

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7. AUTHOR CONTRIBUTIONS

CLQ: methodology, investigation, writing (OD), visualisation. TEF: conceptualisation, methodology, investigation, resources, writing (RE), visualisation, supervision, funding acquisition. LT: methodology, software, validation, formal analysis, data curation, writing (RE). APS: resources, writing (RE), project administration. LP: Formal analysis, writing, visualisation (RE). RD: formal analysis, writing (RE). AVC: conceptualisation, resources, writing (RE), supervision, project administration, funding acquisition.

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