



Drivers of shoreline change on Pacific coral reef islands: linking island change to processes

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Abstract

Reef islands are considered highly vulnerable to the impacts of anthropogenic climate change. While existing studies provide evidence of high dynamism and predominant stability over recent periods of sea-level rise, efforts to statistically link recorded morphological changes to processes are limited. We analyse shoreline changes across an expansive region of diverse oceanographic and climatic conditions and assess those observations relative to the processes potentially driving change. This record comprises 568 islands from 42 atolls spanning the western to the central Pacific Ocean from the Federated States of Micronesia, Marshall Islands, Kiribati and Tuvalu, and is one of the first robust attempts to statistically attribute the drivers of observed island changes within the past half-century. Our analyses demonstrate that island change and a range of its potential controls, including oceanographic, climatic and local-scale morphometric characteristics of reefs and islands, are not correlated, underscoring that no single variable could predict a uniform response across the study islands. The lack of association between sea-level rise and shoreline change on this large sample of islands addresses the common notion of a linear relationship between rising sea levels and magnitude of erosion in reef island systems. We emphasise the critical need to move from simplistic assessments of island change, highlight the importance of incorporating multiple predictors and the need for more computationally robust models.

Keywords Coral reef islands · Atolls · Shoreline change · Pacific Ocean

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Introduction

Low-lying coral reef islands are considered physically sensitive to the impacts of anthropogenic climate change. Rising sea levels are considered to be a key threat and are projected to destabilise reef island systems through chronic erosion, increased flooding of low-lying areas and saline intrusion into the freshwater lens, rendering them uninhabitable in coming decades (Dickinson 2009; Storlazzi et al. 2018; Oppenheimer et al. 2019). Furthermore, ocean warming and changes in ocean chemistry are expected to degrade reef health and growth, consequently affecting sediment supply critical for island persistence (Perry et al. 2008; Eyre et al. 2018; Cornwall et al. 2021; Duvat et al. 2021a). Observations of the physical dynamics of reef islands across multi-decadal to centennial timescales, primarily using remotely sensed data, have highlighted the ability of these landforms to adjust morphologically with changing environmental boundary conditions (see McLean and Kench 2015 and

Duvat 2018 for review). These studies have collectively examined a large sample of mid-ocean atoll reef islands ($n \sim 1000$) across the Pacific and Indian Oceans. They have shown that, while islands are mobile, the majority have persisted on their reef surfaces and, in many cases, grown in planform area since the mid to late twentieth century, a period of documented sea-level rise. However, observations of island expansion or stability in land area are not ubiquitous. Some studies, which examined a comparatively small number of barrier or fringing reef islands ($n \sim 50$), such as in the Solomon Islands (Albert et al. 2016) and across lagoon islets in New Caledonia (Garcin et al. 2016), have reported widespread erosion and island loss during the past half-century. While complicated localised factors at these sites remain poorly resolved, these changes have been attributed to accelerated sea-level rise rates and altered wave climate suggesting a linear relationship between increasing sea levels, wave energy and the magnitude of erosion. Analysis across 20 islands of Peros Banhos atoll also showed a linear relationship highlighting energetic coastlines fronted by broad reef flats tend to erode through time (Wu et al. 2021).

In a review of reef island change studies, Duvat (2018) highlighted the need to undertake analysis over large spatial extents using standardised protocols of recording island change and moving from ‘assessment to attribution’. The collective record of reef island studies, while being extremely valuable in providing quantitative analysis of shoreline change, is spatially fragmented across a wide gradient of oceanographic and climatic processes, including rates of sea-level change and wave climate (Church et al. 2007; Meyssignac and Cazeuve 2012; Reguero et al. 2015). Consequently, to date, the robust identification of the mechanisms driving island change has been elusive and limited to the direct impacts of anthropogenic interventions and event-based observations such as storms causing marked geomorphic changes on reef islands (Blumenstock 1958; Biribo and Woodroffe 2013; Ford and Kench 2014; Duvat and Magnan 2019; Holdaway et al. 2021). Despite widespread concern regarding the impacts of sea-level rise (SLR) on the persistence of reef islands, efforts to statistically link SLR to documented rates of island change remain limited (Wu et al. 2021), and the notion of a simplistic linear relationship between sea-level rise and erosion persists and remains largely untested (Dickinson 2009; Albert et al. 2016; Nunn et al. 2017).

The Pacific Ocean is home to the vast majority of atolls. Its marked gradients of climatic and oceanographic processes provide an excellent laboratory to explore the drivers of island change. Moreover, while studies on reef island dynamics across small spatial extents struggle to isolate wave energy from SLR and examine variabilities at inter-atoll and inter-archipelagic scales, a region-wide analysis allows greater scope to evaluate these different drivers. This study compiles an extensive dataset of multi-decadal

shoreline changes on 568 reef islands from 42 atolls in the western and central Pacific spanning latitudinal gradients in wave energy (Durrant et al. 2014), ocean storm frequency (Knapp et al. 2018) and rates of sea-level rise (Becker et al. 2012) (Fig. 1, Fig. 2).

Previous studies have highlighted the role of local-scale morphological controls in island change by regulating sediment transport pathways and, consequently, patterns of accretion or erosion along island shorelines (Kench and Brander 2006; Ortiz and Ashton 2019; Shope and Storlazzi 2019; Wu et al. 2021). Thus, in addition to examining shoreline changes along the gradient of environmental conditions in the Pacific, this study also investigates the role of local morphological controls in dictating patterns of island change. Using high-resolution remotely sensed imagery, a range of morphometric properties of islands and their underlying reef platforms, such as reef width, distance from reef edge, island shape and size are quantified for the study islands.

Finally, a series of statistical analyses are performed to examine the existence of any linear relationships between these regional and local-scale environmental and morphological controls and documented island change.

Climatic setting and environmental gradients in the Pacific Ocean

The study examines atoll reef islands in the central and western Pacific that span approximately 40 degrees in longitude (~ 4500 km) and 25 degrees in latitude (~ 2800 km) (Fig. 1). Across this large expanse of the Pacific Ocean, there are clear gradients in the environmental conditions that potentially influence island change.

Sea level

Tide gauge measurements from the west and central Pacific provide a near-continuous record of sea levels since the 1950–1970s (Becker et al. 2012). However, these records are limited to a few locations with just seven active tide gauges combined across FSM, RMI, Kiribati (Gilbert group) and Tuvalu. Precise satellite altimetry records available since the early 1990s provide a higher spatial resolution record of sea-level rise trends across the Pacific (Ablain et al. 2017; Legeais et al. 2018). These records are spatially variable, with some of the highest rates of SLR located in the western Pacific (> 4 mm/year), about 10° north of the equator across the Federated States of Micronesia (Fig. 2a). Significantly, SLR rates across the study atolls are largely higher than the global mean of ~ 3 mm/year over the past two decades (Ablain et al. 2017; Legeais et al. 2018), with values ranging between 3.19 mm/year (Gilbert Islands, Kiribati) and 5.03 mm/year (FSM, Fig. 2a).

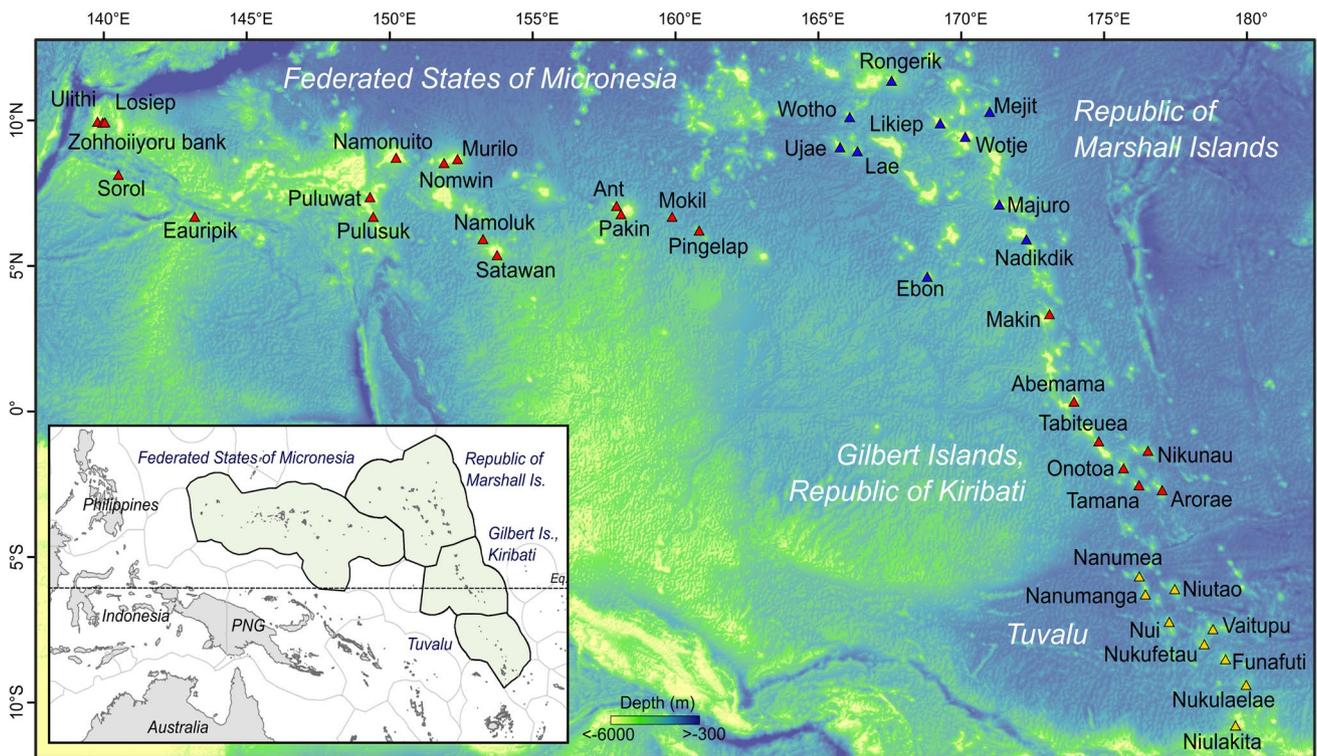


Fig. 1 Location of the 42 study atolls spanning the western to central Pacific from the FSM, RMI, Kiribati and Tuvalu (Points are colour coded by study sources: red: Sengupta et al. 2021a, b; blue: Ford

2012, 2013; Ford and Kench 2014, 2015; yellow: Kench, et al. 2018; Bathymetry data source: GEBCO 2019)

Storm frequency

The frequency of storms varies across the Pacific, with the western Pacific experiencing a high number of storms comparably to the equatorial Pacific (Fig. 2b). Records derived from NOAA’s Best Track Archive for Climate Stewardship (IBTrACS) dataset show the number of storms recorded within 100 km of the study islands during the past century is up to 145 for some islands in the FSM (Fig. 2b; Knapp et al. 2010, 2018). While cyclogenesis is not active in the equatorial zone (between 5°N and 5°S), the atolls in the northern and southern regions of the Gilbert Archipelago are occasionally affected by long-period swell events generated by distant storms (SPREP 2004; Hoeke et al. 2013; 2021).

Wave climate, tidal conditions and precipitation

A high-resolution (~4 arcmin) wave hindcast spanning 1979 to 2014, generated using the WaveWatch III model (Durrant et al. 2014), shows significant latitudinal and longitudinal variations in wave climate across the Pacific. While largely storm free, the equatorial region is dominated by trade winds that generate occasional swell (Bosserele et al. 2015); the western Pacific is a high-storm frequency belt with high

wave energy recorded across atolls of the FSM. Results from this hindcast show that the maximum significant wave height (Hs max) ranges between ~ 3 m (atolls of Gilbert Islands, Kiribati) and ~ 10 m (atolls of FSM), and the 99th percentile of wave energy flux (CgE) varies between 8 kW/m (atolls in the southern Marshall Islands and Gilberts) and 68 kW/m (atolls in west FSM and north Marshall Islands) (Fig. 2c, d).

In atoll settings, tidal range, in conjunction with reef width and depth, plays a crucial role in defining the period and degree of interaction of wave energy with island shorelines (Kench and Brander 2006; Beetham et al. 2016). The FES2014 (Finite Element Solution 2014) is a tidal model that estimates tidal range globally. It shows tidal range across the study atolls varies between 0.75 and 2.06 m, with some of the largest values in the equatorial Pacific, in the Gilbert Islands, Kiribati (Carrere et al. 2016; Lyard et al. 2021; Fig. 2e).

Rainfall has been shown to strongly influence vegetation growth and soil development in the Pacific and is closely associated with the varying susceptibility of atoll islands to coastal erosion (Fosberg 1949; Stoddart 1983; Mueller-Dombois & Fosberg 1998). Rainfall across the Pacific is highly variable. Data from the ECMWF (European Centre for Medium-Range Weather Forecasts) ERA5 model (C3S, 2017) show average monthly precipitation across the study

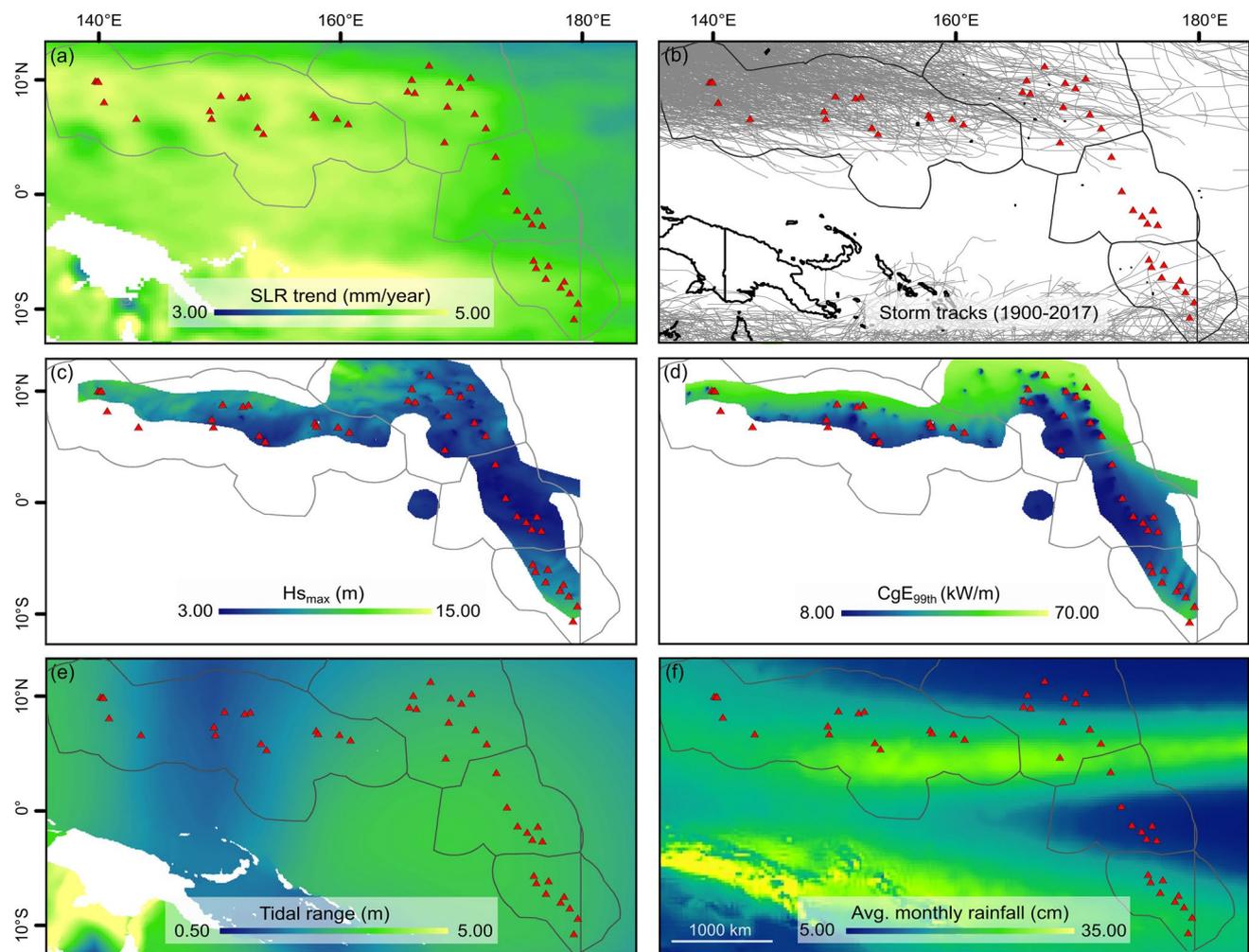


Fig. 2 Oceanographic and climatic setting: **a** sea-level rise rate in the altimetry era (1993–2020) (Ablain et al. 2017; Legeais et al. 2018). **b** Storm tracks between 1900 and 2017 derived from NOAA’s IBTRACS dataset (Knapp et al. 2010, 2018). **c, d** Wave climate variables, maximum significant wave height (H_s) and wave energy flux

(CgE_{99th}) derived from 4 arcmin resolution WaveWatchIII hindcast (1979–2014) (Durrant et al. 2014). **e** Tidal range (Carrere et al. 2016; Lyard et al. 2021). **f** Average monthly precipitation (C3S, 2017). Red triangles indicate the location of the study atolls

atolls ranges between 12 (atolls of Gilbert Islands, Kiribati) and 31 cm (atolls of the Marshall Islands) (Fig. 2f).

Oceanographic and climatic conditions strongly vary across the study atolls, with latitudinal and longitudinal gradients in SLR, wave climate, tidal conditions and precipitation. While most variables are largest at higher latitudes and towards the west, some of the largest tidal ranges are observed in the central equatorial Pacific.

Methods

Shoreline interpretation, uncertainty and analysis

We analysed multi-decadal shoreline change records from 568 reef islands across 42 atolls from the Federated States

of Micronesia (FSM) (Sengupta et al. 2021a), Marshall Islands (Ford 2012, 13; Ford and Kench 2014, 2015), Gilbert Islands, Kiribati (Sengupta et al. 2021b) and Tuvalu (Kench, et al. 2018). The analysis window was between 1944 and 2018 (see Supplementary Document for a summary of study atolls and maps illustrating their planform characteristics). Consistent with previous multi-decadal reef island change studies, the edge of vegetation was used as the shoreline proxy in this dataset (McLean and Kench 2015; Duvat 2018). It is easily identifiable across all sources of remotely sensed imagery and is not sensitive to tidal and seasonal fluctuations unlike the toe of the beach or high-water mark. Shorelines were manually digitised within ArcGIS at a uniform scale of 1:1000. The uncertainty in shoreline position was calculated based on Romine et al. (2009), by taking the root sum of square of interpretation

error, rectification error (Root Mean Square Error) and pixel error. The total error in shoreline positions in this dataset was within 4.0 m (Ford 2012, 2013; Ford and Kench 2014, 2015; Kench, et al. 2018; Sengupta et al. 2021a, b).

The Digital Shoreline Analysis System (DSAS) is an ArcGIS extension (Thieler et al. 2009), widely used to analyse shoreline changes from records of multi-temporal shoreline positions. Transects were cast at 10-m intervals across the shorelines, and the rate of change or ‘end point rate’ (EPR) at each transect was calculated (95.5% confidence interval) by taking the net distance between the oldest and latest shoreline (Net Shoreline Movement) normalised by elapsed time. The uncertainty of EPR was calculated for each transect as the summation of squares of shoreline uncertainties divided by the period of analysis (Thieler et al. 2009). The transects with positive upper and lower intervals of EPR were classified as showing statistically significant accretion, negative upper and lower intervals were classified as showing erosion, and the remaining transects were classified as showing no significant change (Ford 2013).

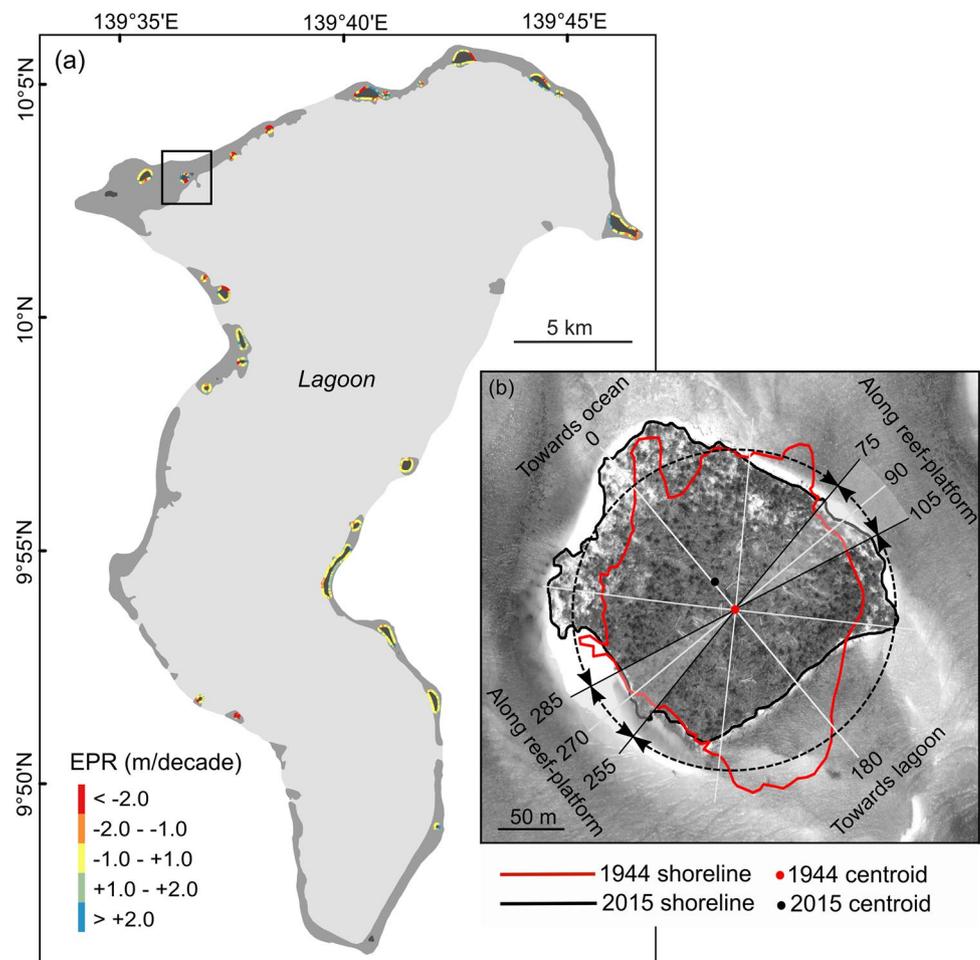
For island-scale analysis, the shoreline change rate on each island was measured by averaging the shoreline change

rate (EPR) across all transects cast within an island (Fig. 3a). The net outcome of local-scale shoreline changes around an entire island may result in a change in the position of the island (i.e., migration across the reef platform) and has been identified as a common response of islands to increasing sea levels (Cowell and Kench 2001; Webb and Kench 2010; Duvat et al. 2017; Masselink et al. 2020). The magnitude of migration is recorded as the distance between temporally consecutive island centroids and provides the means to document net positional change of the study islands. The direction of migration is recorded with respect to the ocean reef edge and the rate of migration is determined by normalising the documented magnitude with time (Fig. 3b).

Quantification of predictor variables and statistical analysis

A suite of 25 variables, detectable using remote sensing methods (summarised in Supplementary Table 1), were examined to explore their influence on island shoreline change and test the existence of a correlation with the

Fig. 3 **a** Shoreline change rates (end point rate (EPR)) are calculated by casting transects at 10 m intervals across island shorelines: example of shoreline change rates (EPR) across islands of Ulithi Atoll, FSM. **b** Migration rates are quantified as the distance between two temporally consecutive centroids normalised by time. The direction of migration is estimated with respect to the ocean reef edge



magnitude of island change. These variables reflect oceanographic and climatic conditions across the study atolls (SLR rate, wave climate including significant wave height and wave energy flux, tidal range and precipitation), and the diverse morphological characteristics of the study islands and their underlying reef platforms.

Properties such as reef width, distance from reef edge and island shape (circularity ratio) that are known to influence wave energy dissipation and interaction with shorelines (Kench and Brander 2006; Ortiz & Ashton 2019; Shope & Storlazzi 2019; Rankey, 2011) are quantified using the high-resolution imagery. Of note, these variables have also been used to test ‘island vulnerability/robustness’ in a recent study (Duvat et al. 2021b).

Vegetation is known to act as natural buffer, reducing sediment loss, preventing overwash and protecting coastlines from erosion (Kaufman and Gallaher 2011; Silva et al. 2016; Mcleod et al. 2019; Salmon et al. 2019; Gracia et al. 2018). The normalised difference vegetation index or NDVI (Weier & Herring 2000) derived from reflectance values of visible and near-infrared bands of multispectral datasets is a measure of vegetation greenness and is used to quantify vegetation density and changes in plant health (Ingram & Dawson 2005; Liu et al. 2013; Mancino et al. 2014; Pravalie et al. 2014). In this study, we computed NDVI for our study islands using the cloud computing platform Google Earth Engine (see Supplementary Document S1 for further details).

Levels of anthropogenic modification to island shorelines and islands’ local position (windward/leeward) are included in the dataset as categorical variables. Existing studies have highlighted both the direct and indirect roles of anthropogenic modifications in dictating shoreline response (Gilie 1993; Webb and Kench 2010; Ford 2012; Biribo and Woodroffe 2013; Duvat and Magnan 2019; Holdaway et al. 2021). Likewise, the location of islands on an atoll has been suggested as a determinant of accretionary or erosional trends (Duvat and Pillet 2017; Shope and Storlazzi 2019; Wu et al. 2021). In this study, we compare the variability of shoreline changes across various levels of anthropogenic modification (i.e. high, moderate or none) and across islands perched on windward vs. leeward rims of atolls.

Finally, we also include the presence of exposed beachrock as a categorical variable. Beachrock are lithified carbonate sediments found in the intertidal zone, that have been used as indicators of past positions of shorelines (Cooper 1991; Kench et al. 2023). While the presence of exposed beachrock on the reef flat surrounding an island may indicate shoreline retreat, they have also been shown to diminish shoreline erosion by acting as a natural barrier (Stoddart and Cann 1965; Mauz et al. 2015; McCutcheon et al. 2017). Indeed, the reconstruction of paleo-shorelines from beachrock goes beyond the period of analysis;

nevertheless, in this study, we analyse the variability of shoreline change on islands with or without the presence of this geomorphological feature that were distinctively identified from high-resolution imagery.

Of note, this set of variables analysed in our study is not an exhaustive list of all possible factors controlling island change and is constrained by the logistic limitations of a remote sensing-based analysis for a large spatial extent. We are unable to include sedimentary characteristics at local scales that play a key role in defining island response (Dawson et al. 2014; Perry et al. 2011, 2015; Morgan and Kench 2016; Tuck et al. 2021). However, variables such as an island’s local position (windward/leeward) and storm frequency may act as surrogates for sediment characteristics (Stoddart and Steers 1977; Bayliss-Smith 1988). Supplementary Table 1 summarises the variables identified and quantified at the island scale. A detailed description of methods adopted for quantifying the variables is presented in Supplementary Document S1. Figure 2 shows the variability of various climatic and oceanographic parameters across the study atolls, and a summary of select local-scale morphometric variables quantified across the study islands is presented in Fig. 4.

Linear regression was used to examine the relationship between island change and the identified ‘predictor’ variables, with shoreline change rates (Island-averaged EPR) and rates of migration of the 568 islands regressed against each of the variables defining various oceanographic and climatic parameters and island-scale morphometric properties. A correlation matrix was constructed to explore the strength of correlation between the response and predictor variables (Supplementary Fig. 6). When many tests are conducted the type-I error rate is inflated, we have not used familywise corrections and report the raw *p*-values. For island-scale properties that were recorded as categorical variables, *t*-tests were conducted to examine the difference in mean rates of change across various island groups. All statistical tests and evaluations were conducted using R (version 4.0.2; R Core Team 2020).

Results

Shoreline changes across the western to central Pacific

Analysis of shoreline changes from 113,866 transects across 568 study islands from the western to central Pacific show 39.14% of transects were characterised by statistically significant accretion, 27.03% by significant erosion and 33.83% showed no significant change. The average rate of shoreline change was 0.51 m/decade, which led to a net increase of 444.63 ha ($4.45 \times 10^6 \text{ m}^2$, ~2.25%) of land area across the

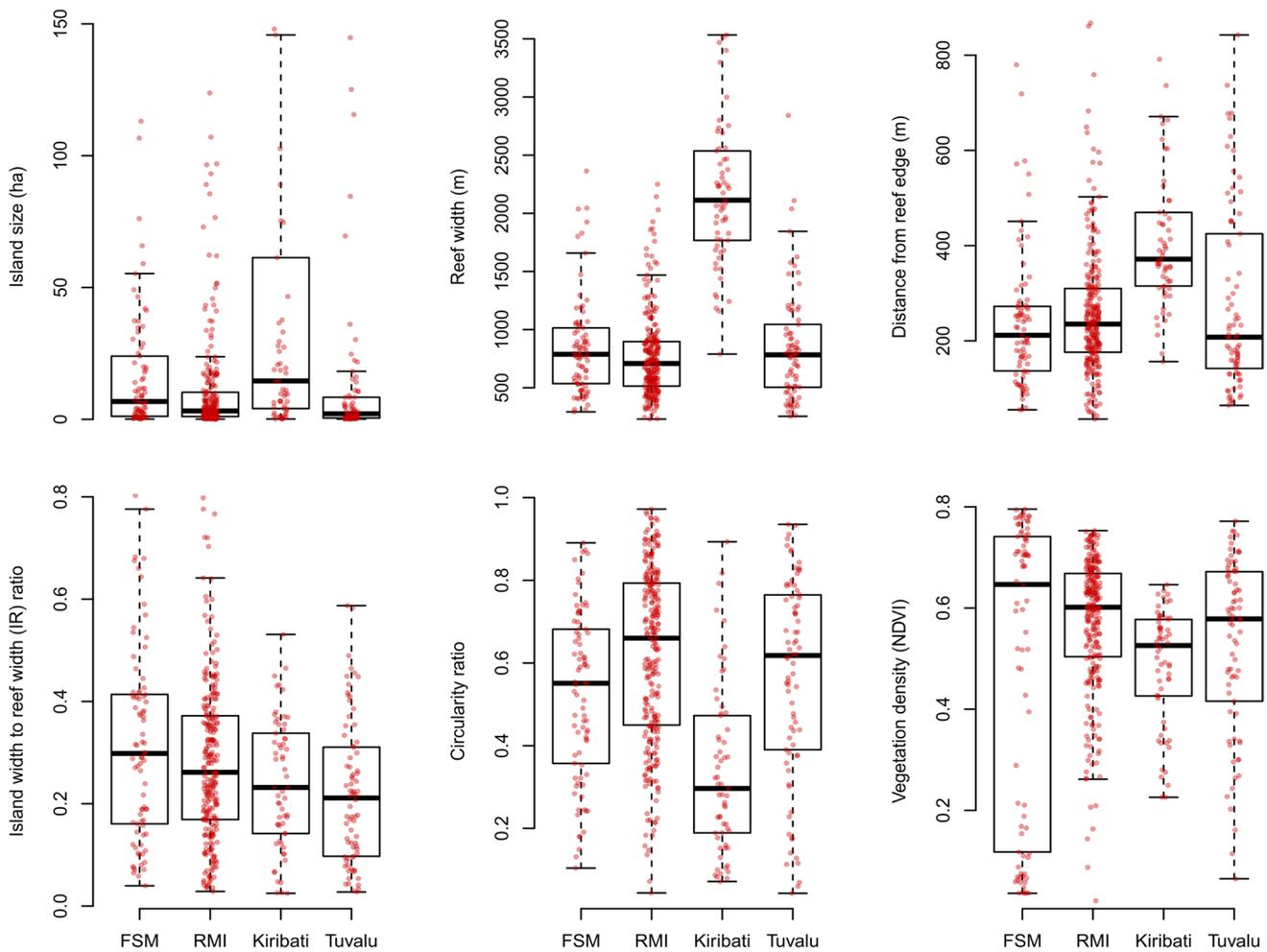


Fig. 4 Summary of select morphometric variables quantified at the island-scale across the Federated States of Micronesia (FSM), Marshall Islands (RMI), Gilbert Islands (Kiribati) and Tuvalu. Points (jittered) indicates values for individual study islands. The full suite of variables is presented in Supplementary Table 1

study islands. The highest island-averaged rate of accretion (4.93 m/decade) was observed on Sorol 2 in FSM, while the largest island-averaged erosional rate (-3.39 m/decade) was observed on Tabiteuea 32 in Kiribati (Fig. 5).

Analysis of positional changes of islands studied showed that migration occurred predominantly lagoonward, with 51.60% of islands migrating towards the lagoon (Fig. 5c). The average rate of migration of these islands was 2.91 m/decade. Oceanward migration was observed in 33.91% of the study islands while 14.49% migrated along the reef platform. The average rates of migration on these subsets were 1.75 m/decade and 3.19 m/decade, respectively.

Linking potential controls to island change

There was no strong association ($R^2 < 0.01$) between the suite of oceanographic (including sea-level rise) and selected climatic variables and recorded changes on reef islands (i.e.

terred) indicates values for individual study islands. The full suite of variables is presented in Supplementary Table 1

island-averaged rate of shoreline change and rate of migration) (Fig. 6). Likewise, tests for local-scale morphometric parameters showed no strong association ($R^2 < 0.01$) between individual variables and island change (Fig. 7). Of note, shoreline change rates on the subset of ocean-facing shorelines also show no strong correlation with the selected variables (Supplementary Fig. 5). Supplementary Fig. 6 presents a correlation matrix illustrating the strength of correlation between various response and predictor variables.

For the categorical variables, boxplots (Fig. 8) show the distribution of shoreline change rates across the study islands. Islands with high anthropogenic modifications are the least dynamic, with low variability, low island-averaged rate of change (0.40 m/decade) as well as a low rate of migration (1.11 m/decade). Rates of shoreline change differ significantly between islands with and without exposed beach rock (BR) (average rate on BR_{present} = 0.32 m/decade, average rate on BR_{absent} = 0.11 m/decade; p -value < 0.01;

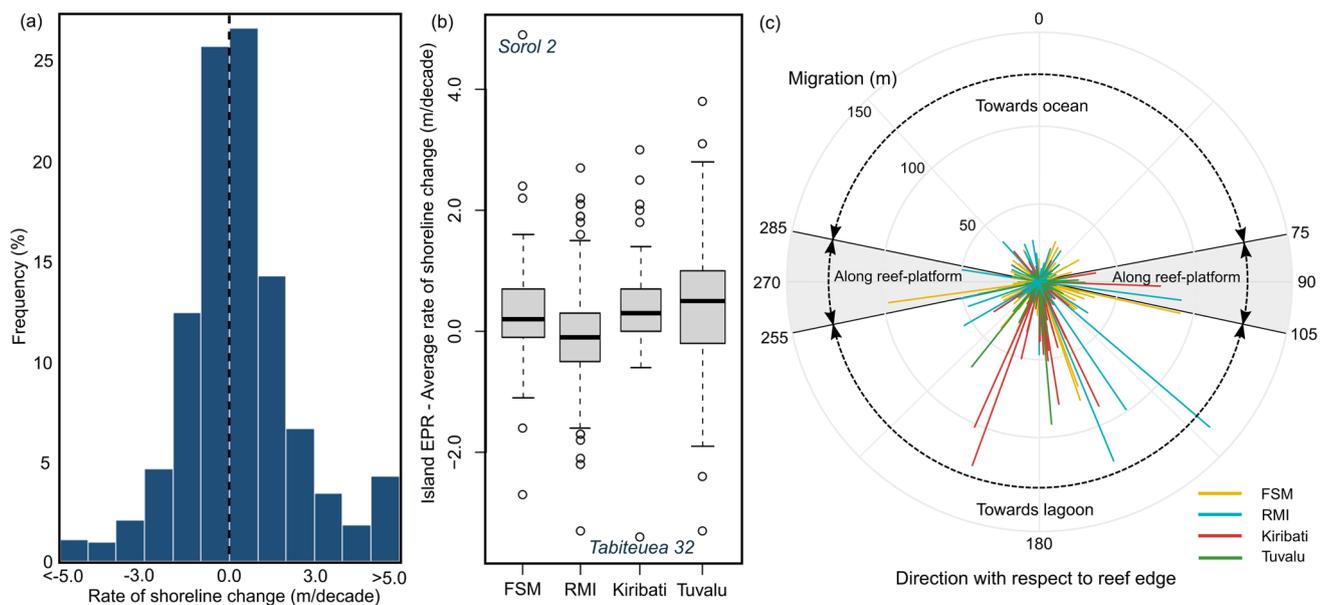


Fig. 5 **a** Distribution of shoreline change rates (m/decade) across the transects of the study islands. **b** Island-averaged rate of shoreline change (m/decade) and **c** net migration (m) across the study islands of

the Federated States of Micronesia (FSM), Marshall Islands (RMI), Gilbert Islands (Kiribati) and Tuvalu

$t = -2.72$, $df = 210.46$). Of note, shoreline change rates of windward (WW) and leeward (LW) islands show no significant difference in their mean values (WW mean: 0.14 m/decade, LW mean: 0.22 m/decade; p -value = 0.49; $t = -0.69$, $df = 217.48$). Rates of migration across these settings are also comparable with an average rate of 2.31 m/decade on windward islands and 1.94 m/decade on leeward islands (p -value = 0.10; $t = 1.67$, $df = 340.89$).

Discussion

This study provided a record of shoreline changes from 568 islands of 42 atolls across the western to central Pacific and is the largest dataset of shoreline change on reef islands to be analysed using a transect-scale method. Statistical relationships between recorded island change and 25 potential environmental, climatic and local-scale morphological characteristics were investigated. These analyses highlight the lack of significant correlation between island shoreline change and these individual variables. This lack of association could arise from several, not mutually exclusive, explanations: (1) significant relationships cannot be detected because the record is too short, sparsely sampled or not sampled at fine enough resolution (issues of statistical power); (2) various thresholds in environmental conditions at which change occurs have not been exceeded; (3) there might be significant relationships with variables that were

not included in this study, such as sediment calibre (Perry et al. 2011, 2015; Morgan and Kench 2016); (4) there are complex interactions between the controls dictating island response and thus a need for more robust models that can represent those interactions.

Shoreline changes across the western-central Pacific

Analysis of 568 islands across the Pacific indicates that most islands have exhibited significant morphological changes over the timescale of analysis (1944–2018). Accretion was observed on 39% of transects, while 27% of transects showed erosion. Aggregated at the island scale, the balance of erosional and accretionary changes indicates a predominance of accretion on islands, with an average shoreline change of 0.51 m/decade resulting in a net expansion of 444.63 ha (~2.25%) of land area.

At the national scale, rates of change have been variable, with study islands in Tuvalu and Kiribati showing the larger average rates of accretion of 0.84 m/decade and 0.77 m/decade respectively, followed by FSM with a rate of 0.48 m/decade and RMI at 0.05 m/decade. There is substantial inter-atoll variability in shoreline change. Atoll-averaged rates ranged from high erosional rates of -0.64 m/decade at Arorae, Kiribati and -0.53 m/decade at Ebon, Marshall Islands to high accretionary rates of 2.18 m/decade at Abemama, Kiribati and 1.96 m/decade at Mokil, FSM. While some of the largest aggregate

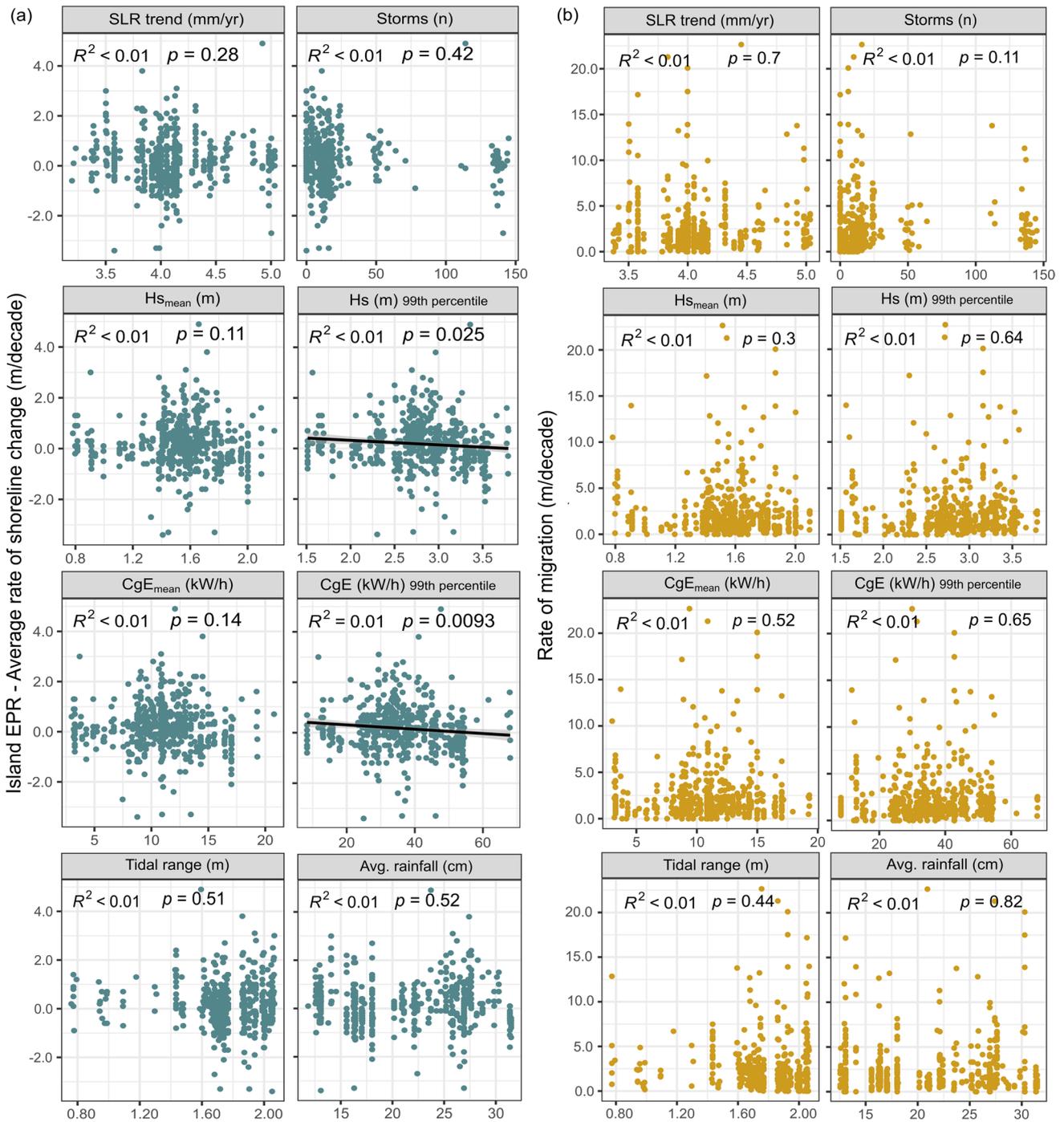


Fig. 6 Various oceanographic and climatic variables vs. **a** rate of shoreline change (Island-EPR) and **b** rate of migration across the study islands from the western to central Pacific (Note: Although $p < 0.05$ indicates statistical significance at $\alpha = 0.05$, this is influenced

by the sample size and there is no strong correlation between the variables ($R^2 < 0.1$); trend lines are not plotted for non-significant associations (i.e. $p > 0.05$))

accretion and erosion have occurred in atolls of the central Pacific, there are no obvious latitudinal patterns of change at the atoll-scale (Supplementary Fig. 7), despite the marked gradient in environmental conditions.

Migration of islands on the reef platform

In addition to net changes in island area, results also show positional changes of islands on their reef surfaces. The

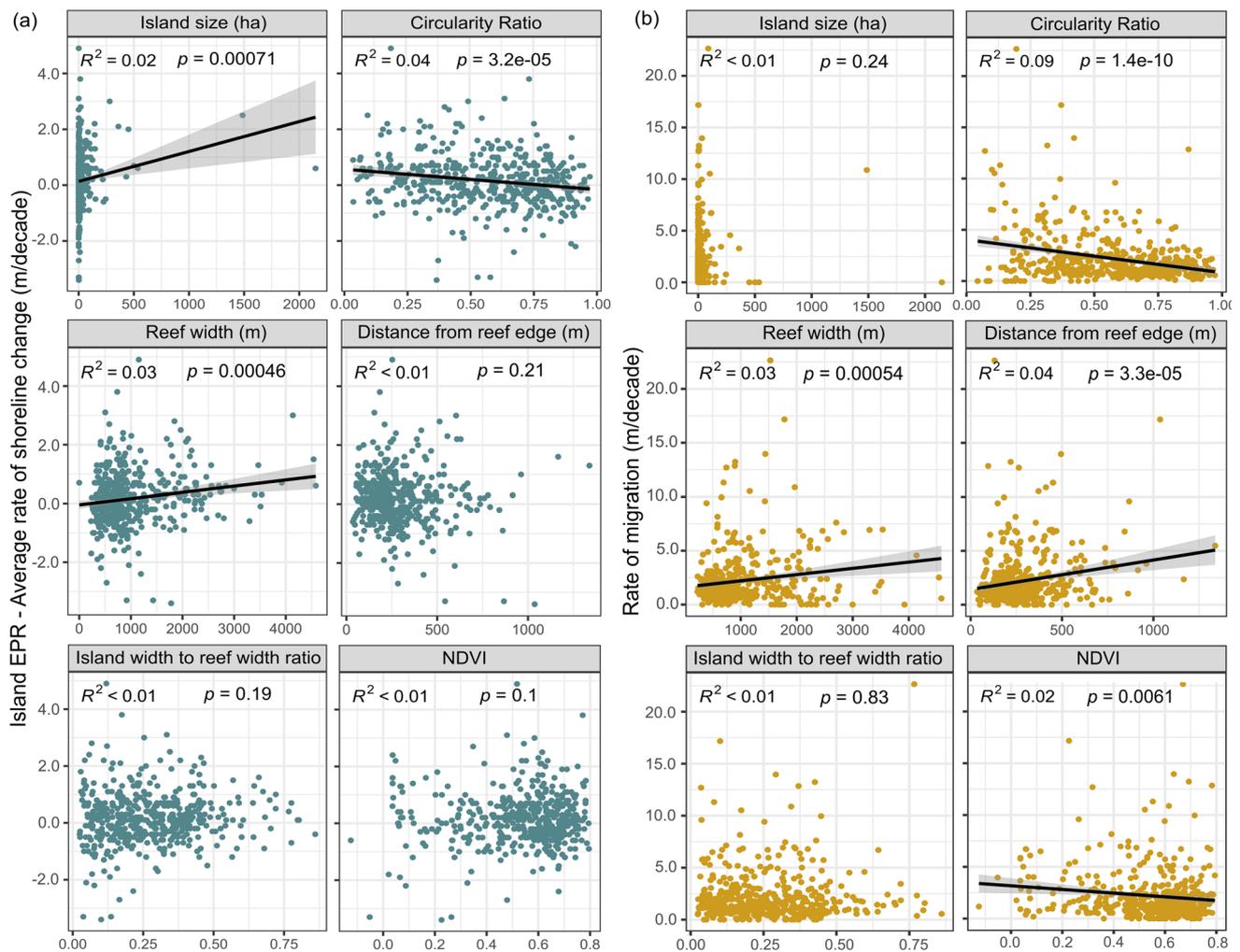


Fig. 7 Selected local-scale morphological variables vs. **a** rate of shoreline change and **b** rate of migration of the study islands. Island width to reef width ratio is a measure of the area covered by an island on the reef platform—i.e. a small island on a wide reef platform has a lower score. Low circularity ratio indicates elongate, irregular islands, higher values indicate a near-circular shape. NDVI (normalised difference vegetation index) is a measure of vegetation den-

sity—sparsely vegetated islands have a lower score; densely vegetated islands have a higher score (Note: Although $p < 0.05$ indicates statistical significance at $\alpha = 0.05$, this is influenced by the sample size and there is no strong correlation between the variables ($R^2 < 0.1$). Trend lines are not plotted for non-significant associations, i.e. $p > 0.05$)

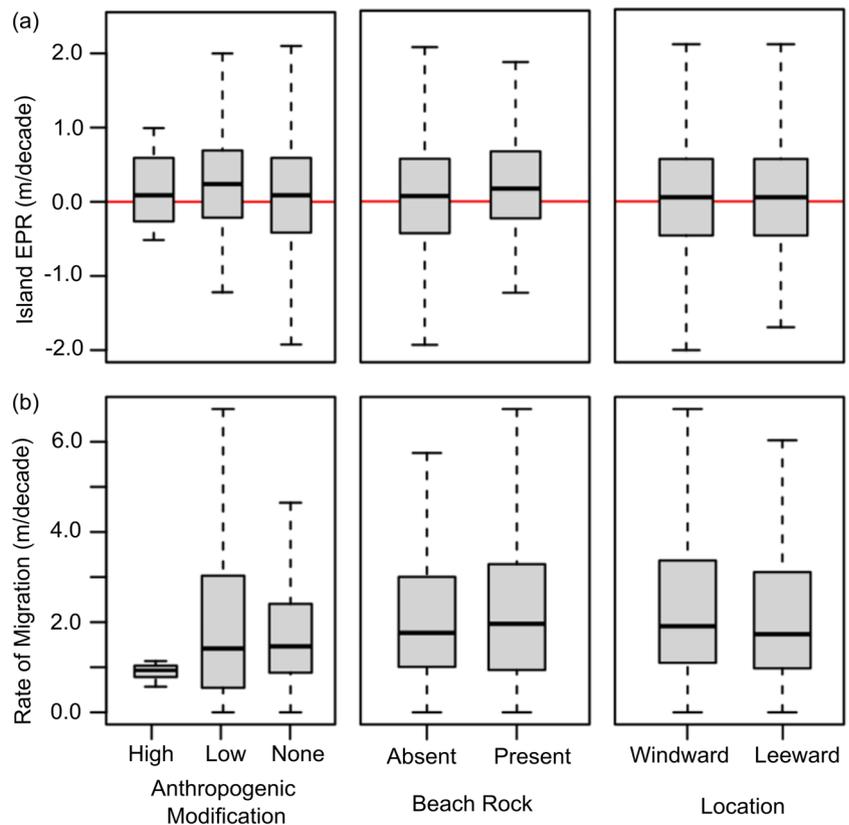
dominant direction of migration is towards the lagoon (52%), though 32% of islands migrated towards the ocean and 14% migrated along the reef platform. The average lagoonward and along-reef migration rates were comparable at ~ 3 m/decade. Lagoonward migration has been observed to be predominant across other atolls in the Pacific and Indian Oceans (Webb and Kench 2010; Purkis et al. 2016; Duvat et al. 2017; Wu et al. 2021), and has been identified as a likely response of islands to increasing sea level in model-based studies (Cowell and Kench 2001; Tuck, et al. 2019; Masselink et al. 2020). The process mechanism proposed for forcing such across reef migration is increased wave energy propagating across coral reef flats under rising sea levels that can remobilise shoreline sediments. Along-reef

migration occurred primarily on elongate islands where spits have accreted and extended. Such changes are likely forced by active wave-driven sediment transport in the littoral shoreline zone. Changes in the rate and/or direction of such alongshore migration may be forced by changes in the wave climate (direction and magnitude). Such observations often lead to the agglomeration of adjacent islands, as recorded in a number of our study atolls (Ford and Kench 2015; Kench et al. 2018; Sengupta et al. 2021a, b).

Characteristic changes across various island classes

Many local-scale characteristics, such as the position of an island on the atoll rim and shoreline modifications, may

Fig. 8 Distribution of **a** island-scale shoreline change rates (m/decade) and **b** rate of migration (m/decade) across the study islands for various local-scale categorical predictor variables



influence patterns of island change (Duvat and Pillet 2017; Duvat and Magnan 2019; Shope and Storlazzi 2019). We examined three such properties captured as categorical variables using remotely sensed datasets, i.e. location of the island (windward/leeward), presence of exposed beach rock and degree of anthropogenic presence. Our results provide insights into the characteristic changes on islands across the various classes that represent their diverse morphological setting.

Shoreline changes on windward vs. leeward islands

Several studies have suggested islands on the windward rim of atolls are distinct in their morphology and sediment characteristics from their leeward counterparts (Stoddart and Steers 1977; Bayliss-Smith 1988). Studies show a potential association between position on the atoll rim and responses of these islands, with windward (WW) islands predominantly characterised by erosion and leeward (LW) islands by accretion (Duvat and Pillet 2017; Shope and Storlazzi 2019; Wu et al. 2021). We recorded comparable shoreline change rates between windward and leeward islands with no significant difference in their mean values. Similarly, while the average rate of migration is comparatively higher

on windward islands than on islands perched on the leeward rim, there is no significant difference between their means. These results highlight that island change has been largely comparable between leeward and windward rims of the atolls across the Pacific. While the degree of morphological changes observed on the study islands over the past half-century may reflect adjustments to changes in the localised process regime, their position on the atoll alone has not been an important determinant.

Presence of beachrock

Beachrock comprises lithified carbonate sediments found in the intertidal zone, which record previous positions of stable beaches (Cooper 1991). While the exposure of beachrock can indicate beach recession (Stoddart and Cann 1965), studies have also suggested that beachrock may protect low-lying islands from erosion (Mauz et al. 2015; McCutcheon et al. 2017). Within our study dataset, 26% of the islands ($n = 145$) had exposed beach rock visible in the intertidal zones and/or along island shorelines, such as around islands of Murilo Atoll, FSM (Supplementary Fig. 8). The presence of beach rock that is detached from the island shoreline is a reinforcing indicator of shoreline change and possibly island migration, and it can be argued that an island that has

a history of change may continue to do so into the future. However, a unidirectional movement may not be expected and shoreline positions may fluctuate subsequently either burying or exposing beach rock (Cooper 1991; Vousdoukas et al. 2007). While our analysis shows that rates of shoreline change on islands with presence of beachrock have been significantly higher, for a comprehensive understanding of how beachrock affects shoreline behaviour, further analysis is required. For example, a sub-sample of shoreline transects that intersect beach rock exposure along island shorelines can be used alongside a high-temporal frequency dataset to track the trend of island shoreline change within these settings.

Anthropogenic modifications

Approximately 20% ($n = 112$) of the islands in the study sample have some form of anthropogenic modification identifiable on high-resolution imagery (e.g. small settlements, airstrips, causeways and shoreline protection structures). Anthropogenic modification of islands can influence island change directly and indirectly. Direct impacts include large-scale land reclamation of highly urbanised islands or the creation of entirely new islands (Webb and Kench 2010; Ford 2012; Biribo and Woodroffe 2013; Duvat and Magnan 2019; Holdaway et al. 2021). Indirect impacts of anthropogenic alterations include modification of shorelines and building of coastal protection structures that alter sediment transport pathways resulting in changes in erosional and depositional zones along island shorelines (Gillie 1993; Kench 2012). This study compared islands with varying degrees of anthropogenic modifications and offers some insights into their characteristic responses. There was a low average rate of shoreline change and a low migration rate on islands with a 'high' level of anthropogenic modification (Fig. 8). Additionally, highly modified islands showed the least variability in rates of shoreline change and migration, highlighting the low dynamism of these islands compared to entirely natural islands with no anthropogenic intervention. However, at the Pacific scale, 'degree of modification' is a broad classification, which limits the identification of complex changes in sediment transport and depositional processes occurring across island margins as a result of anthropogenic interference. Identifying anthropogenic controls on island change requires a more comprehensive dataset with a more refined and nuanced description of the type and scale of modification. Statistical analyses similar to those presented in this study for a sub-sample of islands with a high degree of modification and the identification and quantification of further controls for these islands that account for activities such as mining, causeways, sea walls and degree of reclaimed land might assist in isolating the impact of such structures on observed shoreline changes.

Is sea-level rise a good predictor of island change?

Sea-level rise has been implicated as an important driver of reef island shoreline change. Some local-scale studies have implicated high rates of sea-level rise as a cause of increased erosion and island loss (Albert et al. 2016; Garcin et al. 2016; Nunn et al. 2017). Studies examining archipelago-wide or region-wide changes in atoll islands in the Pacific, which include much larger island datasets, have also identified erosion of some islands (Ford and Kench 2015; Kench et al. 2018; Duvat 2018). However, in those studies, examples of island erosion are the minority, with island accretion/expansion being the predominant morphological response, followed by morphological changes resulting in no net change in island area (McLean and Kench 2015; Duvat 2018). Consistent with these studies, our results also show a predominance of accretion and a tendency of islands to migrate towards the lagoon. However, within existing studies, efforts to statistically link island shoreline change to SLR rates have been limited (Wu et al. 2021). This study addressed this gap by examining the correlation between shoreline changes on islands across the Pacific to rates of sea-level rise at these locations. Using currently available datasets, no significant association emerge between the two and thus indicate SLR alone is a poor predictor of shoreline change at this time (Fig. 6). While it is striking that no individual variable was strongly associated with shoreline change, the lack of a significant correlation between sea-level rise trend and island change is particularly noteworthy, with considerable implications for efforts to forecast island change. We note that while SLR rate is not correlated with island change, these results are entirely based on observations in recent decades with altimetry measurements of SLR available since the early 1990s; therefore, they do not cover the entire sampling span of this study (1944–2018). Likewise, measurements of vertical land motion across the Pacific is sparse and associated with considerable uncertainty and is therefore not incorporated in this study (Ballu et al. 2019). However, our results using precise altimetry measurements that show acceleration of SLR rates since early 1990s illustrate that these high rates have so far not resulted in predictable island change, showing no linear relationship to the magnitude of change observed within our dataset. Consistent with previous studies (Duvat et al. 2021a, b; Wu et al. 2021), our results based on a large sample size and statistical evaluation highlight that any effects of SLR on island physical form may not be expressed directly or linearly with increments of SLR, and there may be a significant lag before morphological responses emerge. Frequent monitoring of shorelines over recent decades may provide insights into SLR signals on island adjustments over short timescales. We also note that while we are unable to detect a relationship between island change and rates of SLR between 3.19 to 5.03 mm/year, this does not discount the possibility that

the higher rates of SLR expected over the coming century of 2.0–6.8 mm/year (RCP 2.6) and 7.5–15.7 mm/year (RCP 8.5) (IPCC, 2021) will have a detectable impact on islands.

It is possible that the effects of SLR are masked by higher frequency perturbations such as storms (Kench et al. 2015; McLean and Kench 2015), and other processes altered by SLR (secondary effects), such as wave transmission across reefs playing a more direct role in island change (Beetham et al. 2016; Duvat et al. 2021a; Wu et al. 2021). Furthermore, local geomorphic setting (island shape, reef width, depth), along with SLR and wave energy, may synergistically determine the magnitude and pattern of shoreline changes on reef islands (Mandlier and Kench 2012; Albert et al. 2016; Ortiz and Ashton 2019; Shope and Storlazzi 2019). Consequently, we emphasise that statistically attributing SLR to island change requires robust models, such as those using machine learning algorithms that can handle large datasets, incorporate multiple variables, and examine complex interactions between drivers and island change.

Conclusions and implications for future efforts to understand the attribution of island change

This study provides the compilation and analysis of a large-scale high-resolution shoreline change record consisting of 568 islands on 42 atolls spanning the western to the central Pacific Ocean. The islands span a broad gradient of environmental conditions, including considerable variations in sea-level rise, wave climate and storm frequency. We use this dataset to provide one of the first attempts to attribute observed shoreline changes to processes statistically. Additionally, a number of local-scale parameters that define the diverse morphology and characteristics of the islands and reef platforms were quantified, enabling the examination of their relationship to documented island change.

The analysis of shoreline change highlight that most islands have undergone physical changes over the past half-century, with a mean net accretionary rate across all islands of 0.51 m/decade. Transect analysis indicates that island shorelines predominantly experienced accretion (39%) or remained relatively stable (34%), with a smaller proportion (27%) exhibiting erosion. Lagoonward movement on the reef platform was predominant and observed on 52% of the islands with a relatively high rate of ~ 3 m/decade.

Results from statistical analyses showed no strong associations between island change and individual environmental drivers (e.g. SLR, significant wave height, wave energy flux) as well as reef and island morphological characteristics (e.g. size, shape, reef width). The categorical variables in this dataset provided insights into characteristic responses of islands at diverse settings and various degrees

of anthropogenic modifications. Attributing a process or geomorphic characteristic as a control of island change in a large-scale remote sensing observation-based study has limitations; some key predictors such as substrate characteristics, sediment budget and highly resolved wave interactions with shorelines cannot be investigated. However, the size of the dataset alongside a range of predictors quantified using remote sensing offered the opportunity to evaluate correlations between these potential drivers and island change.

While the outcomes from this study highlight the predominant trend of accretion and lagoonward migration across diverse environmental and morphological settings, results from statistical analyses underscore the complex relationships and interplay between a range of processes regulating the magnitude and patterns of island change. We emphasise the need to move from simplistic assessments of causes of island change to methods that are robust in handling large, complex datasets, can incorporate multiple controls and enable a holistic analysis of process mechanisms driving shoreline changes on coral reef islands.

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Data Availability All relevant data are provided in the supplementary material. Source data are available from the corresponding author on request.

Declarations

Conflict of interest The authors declare no competing interests.

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