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Island change framework defines dominant modes of atoll island dynamics in response to environmental change

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Climatic change threatens the persistence of atoll islands and the cultural and ecosystem services they support. However, adaptation and ecosystem management are constrained by lack of knowledge of island-specific transformations. We present an empirically-based island change framework that characterises the physical trajectory of islands, based on high-resolution shoreline analysis on 509 atoll islands in the central Pacific over the past half-century. Using changes in island size and position we identify seven distinct styles of island transformation in the Pacific, including contraction (21.4%), stability (46.1%) and expansion (32.4%), and show that 40% of islands are currently mobile on reef surfaces. Results challenge the framing of islands as erosional, which misrepresents island behaviour and constrains understanding of island futures. The island change framework highlights a broader set of island-specific management considerations, and opportunities, that scale with the style and rate of island change, and provides an empirical basis to inform management.

Global climatic change and local anthropogenic factors threaten the persistence of atoll reef islands and the cultural and natural ecosystem services they support[1,2]. Atoll islands are coherent accumulations of biogenic carbonate sediment, generated from surrounding coral reefs, and deposited on reef flat surfaces, that in mid-ocean atoll states provide the only land for human habitation[1,2]. Atoll islands also support unique communities of flora and fauna that in themselves are critical in maintaining reef island ecosystems[1,3,4].

The concern that reef islands will experience increased flooding and shoreline erosion, become physically unstable, and contract in size, in response to sea-level rise and climatic change over the coming decades, has been highlighted in numerous studies[2,5–8]. Such impacts are projected to contribute to the decline of critical ecosystems and life supporting services, thus threatening the habitability of atoll islands[2,9]. However, empirical evidence to support these assertions is sparse and inconclusive[2,10]. Underpinning projections of island flooding, erosion, and contraction, are assumptions that islands are inert and geomorphically passive structures that will submerge and erode in place in response to rising seas, therefore reinforcing a deteriorating physical trajectory[5,6]. However, a growing number of studies have shown that atoll islands, are physically dynamic landforms that: have changed in size and have migrated on reef surfaces over the past century[11–21], and have exhibited a high degree of dynamism at timescales of seasons[22] to millennia[23].

Beyond the field of atoll island geoscience, the inherent dynamics of islands have yet to achieve broader recognition or be incorporated in short-term (years to decadal) management interventions or longer-term (multi-decadal) adaptation responses that act to conserve cultural and natural ecosystem services. While the possibility of these styles of landform change have been acknowledged in recent summaries of the threat of climatic change on reef islands, it is still widely asserted that islands will become more frequently flooded, and undergo increased shoreline erosion and loss of land[2,7,8]. Indeed, considerations of dynamic changes of entire islands, that may also include positional changes and expansion, are largely omitted in theoretical, or practical, considerations of island vulnerability or future adaptation strategies[24,25].

While decisions regarding habitability involve a complex set of considerations that include life supporting services and cultural values[26,27], we propose that recent advances in resolving island dynamics can be used explicitly to inform locally relevant conservation and adaptation approaches on atoll islands, particularly in non-urban island settings[4]. However, adoption of island physical dynamics in future planning considerations must overcome several constraints. First, the narrative of island erosion, instability, contraction and loss[7,28], mis-represents how islands are responding to environmental change, and normalises island physical trajectories to a single outcome. Consequently, management and adaptation interventions are largely constrained to a suite of generic protective

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measures[25], including nature-based solutions[29–31], that may offset a particular set of immediate threats through buffering and protection to hold the shoreline position, but are potentially maladaptive[32]. The end point in many scenarios is inevitable population migration and island abandonment[33,34], while a broader set of options that incorporate land transformations into short and medium-term management strategies are discounted[28,35–37].

Second, existing analyses of recent and ongoing atoll island change typically aggregate data for entire atolls and nations[14,15,38], which is too coarse-a-scale to support on-the-ground management responses. Beyond descriptive accounts of some types of island adjustment, studies have yet to systematically define the spectrum of island-specific change, which is critical to inform management approaches at short to medium timescales. It has been argued that there is poor information of the on-the-ground changes that communities can expect[39], which has constrained effective adaptation responses to technical and mechanistic solutions. If resolving what successful adaption looks like for island countries is urgent[40], we argue that resolving on-the-ground and island-scale substrate transformations can provide a powerful platform to inform effective adaptation that reflects and incorporates land dynamics and is at the appropriate scale to support community decision-making[39]. In addition, there has been increasing interest in the adoption of nature-based solutions to support adaptation and conservation of critical ecosystems in atoll nations[4,39]. The key to realising beneficial nature-based solutions in reef island settings rests on linking ecosystem-based interventions with the inherent physical processes of local-scale island change[1,4].

Third, beyond assertions that atoll islands will become increasingly unstable, contract in size with increased likelihood of disappearance[2,6–8], there have been a lack of projections on the likely future physical trajectories of reef islands. While a number of studies have modelled island adjustment to sea-level rise, altered wave conditions and sediment supply[41,42], these remain as generalised modes of possible response and there have been few attempts to project likely on-the-ground future changes at the island scale.

Here we present an empirically informed framework of island change based on detailed re-analysis of 112125 shoreline transects from 509 atoll islands from the central and SW Pacific archipelagic nations of the Federated States of Micronesia, the Republic of Marshall Islands, Republic of Kiribati, and Tuvalu (see Methods[43,44], Supplementary Fig. 1). This island sample spans large environmental gradients in wave energy, tidal regime, and rates of sea level change (Supplementary Fig. 2). Our analysis develops an empirically-based framework for characterising holistic island transformations, that details specific styles of island adjustment. Results are discussed in the context of environmental change and future island adjustments. The new framework highlights a number of considerations that challenge conventional understanding of island dynamics, and which provide important context for island and ecosystem management.

Results

Aggregate island change

Our analysis of 509 atoll islands, from 42 atolls, reveals that across the entire dataset total land area increased by 443 ha over the past half-century[44]. At the atoll scale (Supplementary Table 1), eight atolls (19%) had a net loss in land area (mean of −3.24 ha, max of 12.8 ha on Ebon) while 34 atolls (81%) had a net increase in land area (mean of 13.8 ha, max 149.2 ha at Abemama).

Island scale change

Net changes in island area reveal that 21% had reduced in size, 46% showed no significant change, and 32.2% increased in area. Notably, our analysis of 112125 shoreline transects constructed around island shorelines provides finer resolution data on magnitudes and vectors of island adjustment (Figs. 1, 2, and Supplementary Figs. 4–7). A striking feature of this data is that both erosion and accretion was identified on the majority of islands examined (96%, 484 islands, Figs. 1 and 2b–e). Net accretion was identified on 43,703 transects (39% of sample) while net erosion was detected on 30,476 transects (27% of the sample). Only four islands had erosion on all transects with three of these islands being entirely lost from their reef surface. Twenty islands in the sample had transects where no erosion was recorded including the larger islands of Pulawat 2 (8.87 ha) and Wotje 36 (6.53 ha). Of note, four islands were newly deposited on reef surfaces over the window of analysis (Supplementary Figs. 4–7).

The relative balance of erosion and accretion transects is shown to be a reasonable predictor of whether islands had a net increase or loss of land area (Fig. 1b). However, net change in island area results from both the net balance of accretion and erosion transects, and the relative magnitude of change on each transect (Fig. 1c). The data suggest that accretion has occurred in greater magnitude than erosion, particularly on larger islands (Fig. 1c). In addition, analysis of the spatial pattern in transect erosion or accretion governs island positional change (location or shape on reef surface, Fig. 2).

Combining analysis of net changes in island area, and whether islands have shifted position, we identify characteristic modes of island transformation (Fig. 3, Table 1, Supplementary Figs. 8–13). Results identify a group of stationary islands that had not moved position on their reef surface. Three styles of stationary island change are observed (Fig. 3a–c). Where erosion and accretion are balanced around the shoreline, islands remain stationary in location and have no change in area (ST-N, Fig. 3b). This subset of islands represent 30% of the dataset (153 islands). In 13% of cases (67 islands), transect erosion dominated accretion (Table 1), in both magnitude and frequency, resulting in in situ island contraction (ST-C, Fig. 3a). The average size of islands with this mode of response was 2.97 ha (range of 0.1–33.1 ha), the smallest size-group in the dataset (Table 1). Island expansion occurred on 54 islands (10.6% of sample). In such cases, shoreline accretion dominated erosion, and was distributed evenly around shorelines, resulting in

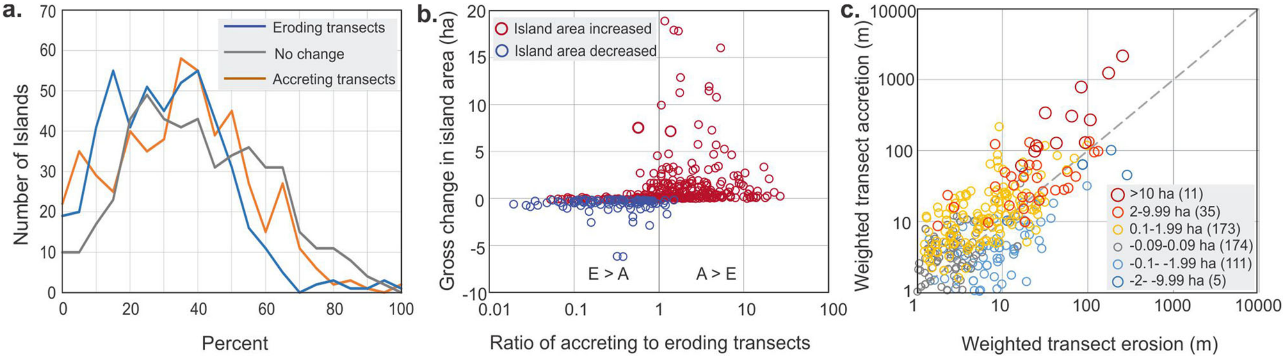

Fig. 1 | Summary of changes in 112125 shoreline transects located on 509 atoll islands. **a** Proportion of transects that eroded, accreted or exhibited no change on islands. **b** Gross change in island area against proportion of number accretion and erosion transects on each island. **c** Weighted balance of erosion and accretion transects on each island, where weighting is based on the actual mean magnitude of erosion and accretion. Source data[44].

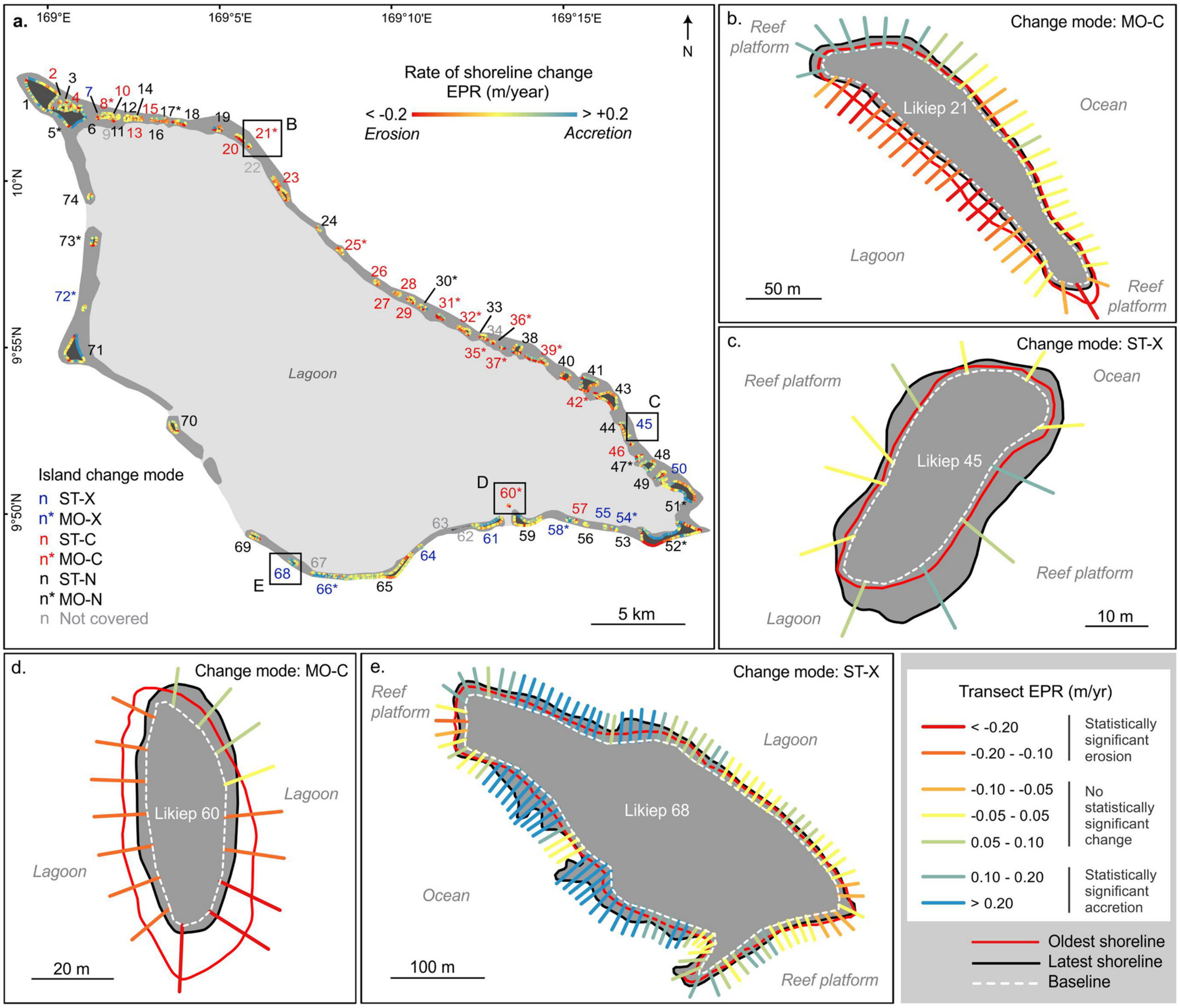

Fig. 2 | Summary of island change at Likiep Atoll, Marshall Islands 1978–2016. **a** Differences in modes of island physical adjustment around the atoll rim (as also defined in Table 1). **b**–**e** Examples of contrasting individual island responses (mobile and contracting (**b**, **d**) and stationary and expanding (**c**, **e**)). The colour gradient indicates statistically significant change (95.5%) high erosion (red) to high accretion (blue) beyond the calculated uncertainty (±0.084 m/year).

islands expanding their footprint on the reef surface while remaining positionally stable (ST-X, Fig. 3c).

Mobile islands occur where the relative magnitude and frequency of transect erosion or accretion dominates and where they are unevenly distributed around an island shoreline, resulting in the reorganisation of shoreline sediments and a net shift in location. In multiple cases, islands have moved well outside their original footprint (Fig. 3d, e). Mobile islands also exhibit three styles of change (Fig. 3d–f). Where erosion and accretion are spatially discrete and are relatively balanced an island can shift its location on the reef surface and retain a constant area (MO-N, Fig. 3e, Table 1). Our dataset shows 78 islands in this category (15%), which are large in area (mean of 102.78 ha). Second, are islands (n = 36, 7.1% of sample) where erosion is most prevalent (51%) compared with accretion transects (19%) resulting in loss of island area and positional movement (MO-C, Fig. 3d, Table 1). Third, are islands (n = 73) where accretion transects dominate (51%) and results in their expansion and positional movement (MO-X, Fig. 3f, Table 1). In multiple cases the extent of new shoreline accretion is substantive and exceeds 100 m (e.g. Abemama Island 6, Supplementary Fig. 11). Coalescence of neighbouring islands and increase in combined island area is an additional mode of island mobility and expansion (Supplementary Fig. 13). This group of islands is small in number (16, 3% of the dataset) but has the largest mean island area (293.9 ha, Table 1). The coalescence of adjacent islands accounts for some of the largest land area gains of up to 30 ha on Abemama (Island 2) and 19 ha on Tabiteuea (Island 4). The total number of islands that expanded in area was 165 (32.4% of total), including islands that remained stationary (54 islands), were mobile (73 islands), or coalesced (16 islands), with an additional 22 islands unable to be classified in the categories of change also increasing in size (Table 1).

Discussion

Our analysis supports improved characterisation of island change, that identifies specific styles and rates of physical transformation on 509 islands in the central Pacific, and is at the necessary scale (entire island and shoreline sectors) to inform on-the-ground coastal and ecosystem management, and longer-term adaptation.

Improved characterization of entire island change

Results highlight the dynamic nature of reef islands and show that erosion and accretion are prevalent processes on almost all islands in the dataset (Fig. 1). Erosion was dominant on only 21.5% of islands (109) leading to island contraction (ST-C, MO-C, and subset of NS types, Fig. 1a, d, Table 1).

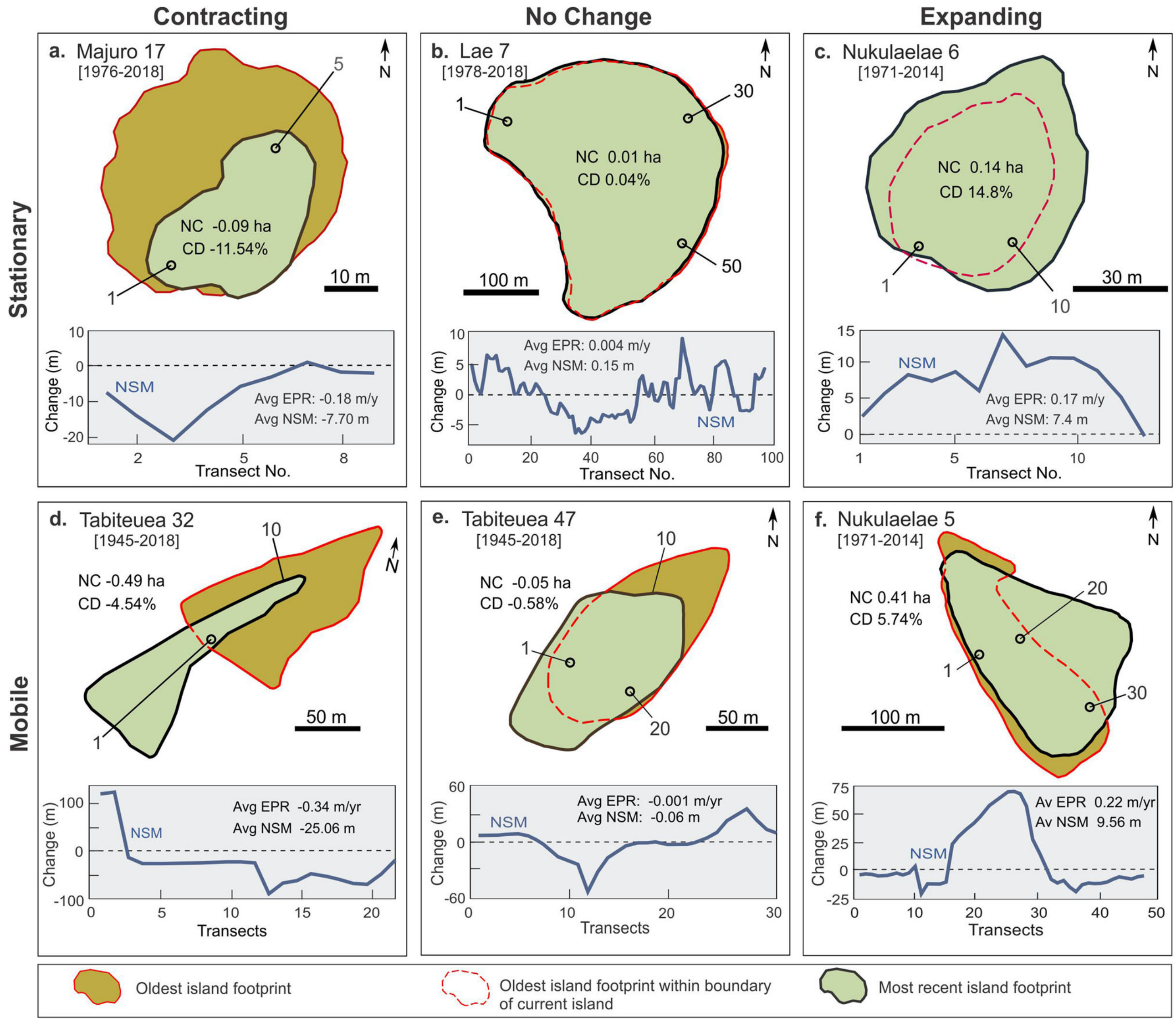

Fig. 3 | Styles of atoll island planform change. Examples of types of physical island change defined by adjustments in island area (expansion to contraction) and island mobility on reef surfaces (**a**–**f**). Timescales of analysis indicted by dates in brackets beneath island name. NC denotes net change in island area (ha) and CD is percent change in area per decade. Inset panels in a-f show transect-scale erosion or accretion around the island shoreline (proportions of statistically significant accretion/erosion are presented in Supplementary Table 1). Further examples of each type of change are presented in Supplementary Figs 8–12.

Table 1 | Summary of changes in 509 atoll islands in the southwest Pacific

Island Change Mode	Island No. [%]	Avg. Island Area (Ha)	% Transects eroded [mean Net erosion, m]	% Transects accreted [mean net accretion, m]	% Transects no change	Migration rate (m/year)	Change per decade (%)
ST-N	153 [30.1]	23.9	23 [6.5]	27 [7.2]	49	<0.2	−1% to 1%
ST-X	54 [10.6]	5.24	11 [5.7]	48 [8.1]	41	<0.2	>1%
ST-C	67 [13.2]	2.97	43 [7.3]	8 [6.9]	48	<0.2	<-1%
MO-N	78 [15.3]	102.78	32 [10.7]	38 [13.4]	30	>=0.2	−1% and 1%
MO-X	73 [14.3]	7.1	24 [9.2]	51 [15.8]	26	>=0.2	>=1%
MO-C	36 [7.1]	3.56	51 [13.8]	19 [11.1]	31	>=0.2	<= −1%
Coalesce	16 [3.1]	293.9	29 [10.9]	45 [18.0]	26	-	-
Not Spec.	32 [6.3]	61.25	31 [6.9]	36 [8.6]	33	-	-

NB: ST = stationary island and MO = mobile island. N, X, and C denote no change, expanding and contracting island area. Not Spec = not specified, which refers to the proportion of islands that did not clearly fit within positional change categories. This small subset had islands that increased (22 islands), remained stable (4 islands), and reduced in area (6 islands).

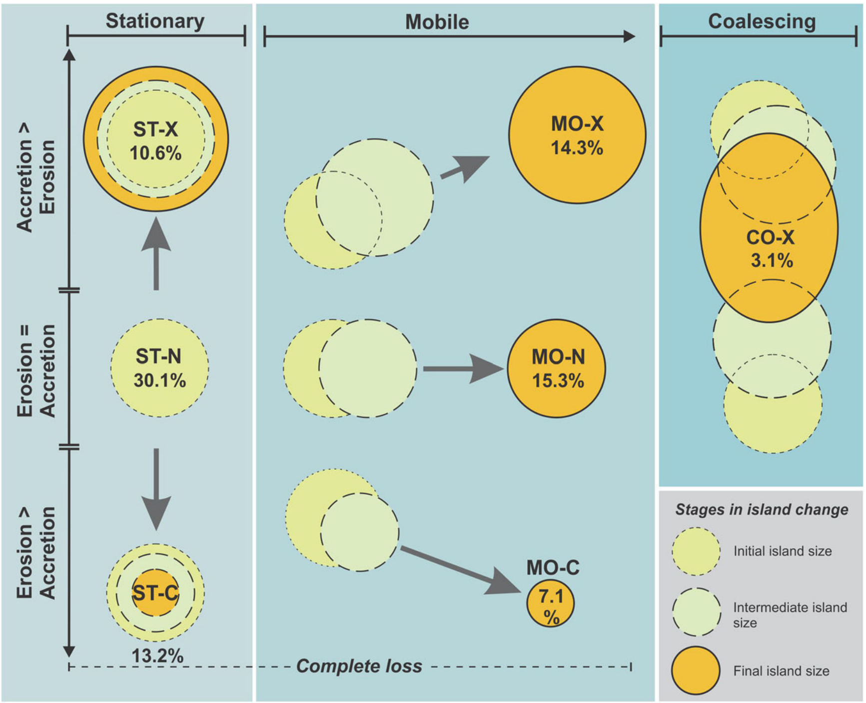

Fig. 4 | Island change framework summarising modes of atoll island physical transformation on reef surfaces. The framework represents the styles of change of 94% of the 509 islands examined from the central Pacific (Table 1). Note: ST = stationary island and MO = mobile island. -N, -X and -C denote no change, expanding and contracting island area respectively; percent values denote the proportion of the island dataset that fits each mode of change. Circular island shape is chosen for illustrative purposes to provide a reference for types of island change.

Of the remaining 400 islands (78.5% of sample), island area remained unchanged (46.2%) or expanded (32.3%), while simultaneously having up to 32% of shorelines affected by erosion. The prevalence of erosion, particularly on islands that have increased in size over recent decades, indicates that erosion is a poor descriptor of whole island behaviour. Consequently, in reef island settings 'erosion' and 'accretion' are terms that should only be used to characterise discrete sectors of shorelines and should not be used to characterise entire island behaviour. Indeed, use of these terms can be misleading as they seldom represent the more complex physical transformations occurring at the island scale (Figs. 2 and 3).

We propose a holistic island change framework (ICF) that characterises island physical dynamics based on two key vectors of island adjustment, first, whether an island is increasing or decreasing in size (i.e. the net balance of island-scale erosion or accretion), and second, whether the island is stationary or mobile on the reef surface (Figs. 3 and 4). The seven styles of island change captured in the ICF are empirically-based and characterise changes documented in 94% of our large island sample ($n = 509$ islands).

Data underpinning the ICF indicates that 20.3% of islands are contracting. Of this sub-sample, half are contracting in place (ST-C) while the remainder are mobile on their reef surfaces (MO-C, Figs. 3 and 4). As previously reported, contracting islands are generally the smallest in the wider sample set (<3.6 ha)[11,13–15]. Islands that have exhibited little change in area over the period of analysis (ST, Fig. 4) comprise 45.6% of the dataset. The ICF highlights two styles of locational adjustment of these islands (Fig. 4). First, 30.1% have remained stationary (ST-N) and have an average size of 23.9 ha. Second, 15.5% of islands have remained stable in area but are mobile (MO-N). This set of islands are among the largest with an average area of 102.8 ha. The ICF indicates that expanding islands, whether stationary, mobile or coalescing, comprise 28% (142 islands) of the dataset. The group of islands that have coalesced (CO-X, 3.1%) comprise the largest islands, at an average size of 294 ha (Table 1, Fig. 4). Notably, island mobility on reef surfaces occurs in 40% of islands examined. Furthermore, our results confirm earlier reports that expansion is common on larger islands, where the dominance and magnitude of accretion is greater than erosion[14,15,17,45].

The empirically-based ICF defines a broader spectrum of styles of island transformation than has previously been described, beyond descriptive observations, and quantifies the frequency of occurrence of each style of change in the island dataset. The modes of island adjustment defined in the ICF are not reflected in national vulnerability or IPCC assessments, in which outcomes such as island erosion, instability, and loss persist[2,7,8], but which only reflect 20.3% of the actual changes taking place in Pacific atolls in our dataset (Fig. 4, Table 1). Notably, 77% of islands are not contracting and the range of styles of adjustment of these islands provide differing ecosystem management and adaptation challenges and opportunities.

Detecting environmental drivers of island change

Projections of how islands will physically change over the coming decades are a high priority to inform ecosystem management and adaptation planning[4,5]. However, modelling attempts are constrained by the lack of a robust relationship between sea level, or other environmental variables and island change[46]. Our observations span the past four to seven decades, a period in which sea-level rise in the central and southwest Pacific (3.55 ±1.33 mm.year^{-1} at Betio to 5.06 ±1.05 mm.year^{-1} at Majuro) has exceeded the global average, and might be expected to have imparted a clear imprint on island transformation. However, comparison of styles of island change against rates of SLR show no uniform or widespread contraction of islands (Supplementary Fig. 3) and no statistical relationship between island change and magnitude of sea-level rise (Supplementary Information 1, Supplementary Fig. 14). Our data shows that mobile contracting and expanding islands are variously co-located within atolls, and on all exposures of an atoll rim (Fig. 2 and Supplementary Figs. 3–7). Lack of a widespread or spatially coherent island contraction signal in our data suggests sea level is currently not detectable as a primary driver of island change[15,19,46]. Consequently, there is currently no empirical basis to use sea level change alone as a predictor of future island change. This finding suggests an additional suite of processes (e.g., wave energy, sediment supply) that influence island change at shorter timescales, and which are themselves modulated by climatic change, are likely to mask or counteract any signal of sea level change[13–15] (Supplementary Note 1).

Future island trajectories

While it is important to be cautious in extrapolating results of analysis of recent shoreline behaviour and island change (Figs. 2 and 3, and

Supplementary Figs. 8–13), and while ongoing research is necessary to better resolve complexity of interacting factors that control change, we argue that our empirical evidence of the recent past currently provides the best insight into what can be expected over the coming decades, in which sea-level rise projections range from 5.25 mm.year^{-1} (SSP1-2.6) to 10.0 mm.year^{-1} (SSP3-7.0) for low and high scenarios respectively[47]. Rates of SLR at the lower scenarios are comparable to those recently experienced in the study region, and it is reasonable to assume that modes and rates of island-specific change observed in recent decades will continue in the near-future (decades). However, rates of sea-level rise are expected to increase over the second half of the century. In addition, rising sea levels, changing ocean water chemistry and temperature are also anticipated to lead to a decline in coral system health including reduced reef growth capacity, structural loss, and reef submergence[48–50], which will increase wave energy at island shorelines[51–54]; and promote alterations in reef sediment generation[55–58]. Collectively these projections of deteriorating reef system health, may alter the physical trajectory of reef islands in several ways. First, as sea levels continue to rise, and wave regimes at island shorelines become more energetic[6,51–54], observed changes in islands are expected to accelerate resulting in increased mobility of islands on reef surfaces[41,42]. Second the magnitude of change may increase. Third, expansion of islands may slow depending on commensurate changes in sediment supply, and whether island adjustment is reliant on an existing (finite) sediment reservoir[55]. Lastly, we also note that where shorelines remain free of anthropogenic modification, island margins are also able to build vertically as sea-levels rise, through wave overwash deposition[41,42]. While overwash sedimentation contributes to island rollover and mobility, increased elevation of island margins can potentially also maintain island freeboard and buffer island surfaces from increased flood risk[42]. We stress that given the complexity of interactions in environmental controls, and future changes in energy regime and sediment supply, ongoing observations, and temporal refinement of observations on islands in our dataset, and elsewhere, is essential to resolve if, and when, islands may alter their current mode of change and adopt an alternate morphological trajectory.

Implications for island-scale management

We recognise that island dynamics and future land availability, as resolved in our analysis, is only one factor that influences island habitability. Indeed, decisions of habitability involve a complex set of social, cultural and biophysical factors[26–28]. However, we argue that improved understanding of how island substrates are transforming can be used more proactively in supporting ecosystem management decisions[1,4] and supporting how island communities might respond to physical environmental change. The empirically-based atoll ICF (Fig. 4) represents a step change in how island adjustment is characterized, providing necessary detail of how specific sectors of islands are transforming. At the simplest level we argue that island-scale knowledge of where land is being lost and gained, which parts of islands are positionally stable or mobile, and the ability to document the rate and magnitude and direction of these changes is valuable to inform decisions on how land can be managed and how different modes of island change can be incorporated into development of nature-based solutions that harness dynamic landform change processes[4].

The ICF also highlights a set of practical realities and considerations for management of islands and their ecosystems that reflect temporal and spatial differences in island physical trajectories. First, very few atoll islands are currently observed to be on a linear path to destruction. Rather, there are a complex range of changes, and more dominant island morphological adjustments occurring, which will continue over the coming half-century. Consequently, management approaches must avoid a singular focus on erosion management and consider a broader set of options that vary between different pathways of physical change (Fig. 4). It is noteworthy that island physical transformations (beyond erosion) are seldom explicitly recognized in coastal management or adaptation analyses, though our data show this is occurring on 77% of islands. Second, all islands experience localized erosion, despite the fact that the majority of islands are stable in area, expanding, and migrating. This highlights the complexity of management considerations within islands where both erosion and accretion need to be acknowledged in designing holistic management approaches that safeguard natural processes and integrity of the entire island. Third, island mobility is common, and presents a distinct management challenge to avoid interventions that fix islands in position that may undermine expansion trajectories. Fourth, the temporal pace of change can be individualized for each island, therefore enabling decisions to occur commensurate with rates and magnitude of change over the coming decades, consistent with adaptive pathways planning[59,60].

Effective local-scale approaches to support the physical resilience of coral reef islands are critical to ensure preservation of their unique cultural and ecological values in the face of unprecedented environmental and anthropogenic change[4,39]. Our results present fine-resolution island-scale analyses of island dynamics that reveal a more complex pattern of change and move beyond simplistic assumptions that islands are eroding. The empirically-based model of island dynamics provides an advance in understanding the range of island dynamic behaviors, and is able to define the on-the-ground changes that impact ecosystems and island communities. This improved knowledge of island-specific changes, and rates of change, can better support the design of nature-based solutions and adaptation approaches that reflect local cultural and ecosystem values, and island-specific morphological trajectories.

Online methods

Field setting and island sample

The study examines detailed changes in shorelines on 509 atoll islands from the archipelagic nations of the Federated States of Micronesia, Republic of Marshall Islands, Republic of Kiribati (Gilbert Chain) and Tuvalu in the central and southwest Pacific Ocean (Supplementary Fig. 1)[43]. The atolls and islands straddle the equator spanning 25 degrees in latitude and 40 degrees in longitude. Consequently, the islands span environmental gradients that include variations in rates of sea level change (~3.55 ±1.33 mm.year^{-1} to 5.06 ±1.05 mm.year^{-1}), and areas of storm frequency and wave energy that are greater in the higher latitudes and lower in the equatorial zone (Supplementary Fig. 2a–d). At the local atoll-scale, islands examined in this study are located on all aspects of atoll reef rims and subsequently vary in relative exposure to oceanic energy. In general, all islands are situated in micro-tidal to lower meso-tidal settings.

Data sources and processing

To examine shoreline changes across our study islands we used collections of historical vertical aerial photographs and recent high-resolution satellite imagery. The aerial photographs from World War II air reconnaissance missions (1940s) and other subsequent surveys from 1960s, 70 s and 80 s were obtained as digital scans from the Bishop Museum, Honolulu, the US National Archives, Washington DC, and the Secretariat of the Pacific Community (SPC), Suva.

Satellite imagery captured between 2013 and 2019 by Quickbird-2, GeoEye-1 and the WorldView series of satellites were used to the provide a modern record of planform island configuration. Images were pan-sharpened, a process by which the high-resolution panchromatic band is merged with lower resolution bands of a multispectral dataset to produce a single high-resolution image (40–60 cm). The swath width of these sensors is between 13 and 18 km and thus, for larger atolls, a number of scenes are often mosaiced to form one seamless image covering the entire atoll. Likewise, many scenes are excluded due to cloud cover and other quality issues and swapped for higher quality scenes. As a result, mosaics are often made of scenes that are captured across multiple days, and thus we refer the shorelines by their year for consistency. The period of analysis spans from 74 years to a minimum of 30 years.

For most atolls only one or two historic aerial photo surveys exist over an extended window between early aerial photos (typically early 1940's) and the advent of high-resolution satellite imagery (post 2000's in most instances). With respect to aerial photographs we acquire every image we can find through exhaustive searches of archives. We endeavour to identify the largest timeframe of analysis possible. It is not possible to know for each island whether our record starts 1 day or 10 years after, or before, a specific environmental perturbation (e.g. storms). Recognising the different time periods of our analysis we normalise the change data (m.year^{-1}) for comparison. Furthermore, our analysis focusses on discerning styles of change and the results, which show heterogeneous responses in most atolls, and that islands with longer periods of analysis have the same range of change as those with shorter periods of analysis, suggest that temporal differences in sampling has little influence on our results.

The aerial photographs were georeferenced using the high-resolution satellite imagery as a source of ground control. Georeferencing imagery of reef islands can be difficult given that most islands are completely vegetated with no anthropogenic presence and therefore do not have any permanent structure to be used as ground control points (GCPs). We used temporally stable natural features around the islands including exposed beach rock, conglomerate in the intertidal zone, or coral heads visible in the imagery as GCPs to enable geo-referencing[20]. A minimum of 10 GCPs were used for each image, and images were transformed using a second-order polynomial transformation.

All shapefiles for the 509 atoll islands examined in this study are available through the Figshare data repository[43].

Shoreline interpretation and uncertainty

The edge of vegetation is the most widely used shoreline proxy within studies on reef island change[14,15]. It is easily identifiable in most remotely sensed imagery and is least affected by image contrast or colour. Additionally, unlike the toe of the beach or the high-water mark, which can fluctuate over short time-periods, the edge of vegetation filters short-term noise and provides a robust basis for shoreline interpretation particularly, when tracking multi-decadal island change. Shorelines for the study islands were manually digitised within ArcGIS with a uniform scale of 1:1000 maintained throughout the digitising to ensure consistency. The uncertainty in the interpreted shorelines (Total error) was calculated as the root sum of square of three sources of error, i.e., pixel error, interpretation or digitisation error and rectification error from georeferencing[61]. Pixel error is given by the spatial resolution of the imagery and interpretation error is obtained by taking the standard deviation of repeated digitisation of the same section of the coast[38]. The Total error (Te) in this record ranged between 1.68 m and 3.53 m. All shape files delimiting the island edge can be obtained.

Shoreline change analysis

The Digital Shoreline Analysis System (DSAS version 4.3) is a widely used tool to analyse shoreline changes from multi-temporal records of planform shoreline position[62]. Available as an extension within ArcGIS, DSAS casts transects at equal intervals perpendicular to a baseline generated by the user. DSAS generates a suite of shoreline change statistics, such as the NSM (Net Shoreline Movement) which measures the distance between the earliest and the most recent shoreline. Recognising that the time intervals of analysis varies between atoll systems (30–74 years) we also calculate the End Point Rate (EPR), which normalises the NSM to compute the rate of change per year. Transects were generated at 10 m intervals along the baselines and a confidence interval of 2σ (95.5%) was used for the calculation of uncertainty in shoreline change statistics. The confidence interval of End Point Rate (ECI) is calculated in DSAS from the summation of squares of individual shoreline uncertainties, divided by the number of years between the oldest and the latest recorded shorelines[62]. We use the uncertainty range (± x m/year, calculated at 95.5% confidence interval) to establish whether change on a specific transect is statistically significant. Where the calculated rate of change on a transect sits above or below the uncertainty range (± x m/year), transects show statistically significant accretion or erosion. Where the rate of change on a specific transect sits within the uncertainty range, transects show no statistically significant change[20]. The net outcome of local-scale shoreline changes around an entire island may result in a change in the position of the island. The net migration of an island is quantified as the Euclidean distance between the geometric centroids of the island shape at the studied points in time. The rate of migration is calculated by normalising this distance with elapsed time. The use of the geometric centroid assures that what we report is a tangible migration of the mean position of an island on the reef platform, and any imbalance in shoreline adjustments is therefore directly accounted for within this calculation. We apply a threshold value of 0.2 m/year to determine significant movement of the island centroid. Values of island movement below 0.2 m/year are classified as stationary. All summary data analysis for each island is available through the Zenodo data repository[44].

Analysis of environment drivers of shoreline change

Our island change data was examined to determine whether relationships were detectable between established rates of shoreline change (EPR and migration) and environment drivers[46]. Environmental variables examined included: rates of sea-level rise as extracted from satellite altimetry data for the region (1993–2020)[63,64]; proximity (within 100 km) and frequency of storms derived from NOAA's Best Track Archive for Climate Stewardship Dataset (IBTrACS, 1900–2017)[65,66], wave characteristics (Hs_{max}, and wave energy flux) derived from 4 arcmin resolution WaveWatch-III hindcast data (1979–2014)[67], and regional variations in tidal range[68] (Supplementary Fig. 2). Environmental variables extracted for analysis was the closest datapoint to each island examined.

Environmental variables were selected from the closest data point available to each island within the datasets presented in Supplementary Fig. 2. Linear regression was used to explore whether relationships were detectable between the primary environmental variables (sea-level rise, storms and wave energy) and rate of shoreline change (EPR), and island migration rates[46].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The authors declare that all shoreline shapefile data is available at https://doi.org/10.17608/k6.auckland.26951893.v1. Summary island-scale analysis of shoreline data is available at https://doi.org/10.5281/zenodo.13701117.

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Author contributions

PK conceived the project; MS, MF led data analysis, PK, MS, MF and SO undertook data interpretation, PK led manuscript development and all authors contributed to manuscript revision.

Competing interests

The authors declare no competing interests.

Additional information

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