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The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific

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ABSTRACT

Low-lying atoll islands are widely perceived to erode in response to measured and future sea-level rise. Using historical aerial photography and satellite images this study presents the first quantitative analysis of physical changes in 27 atoll islands in the central Pacific over a 19 to 61 yr period. This period of analysis corresponds with instrumental records that show a rate of sea-level rise of 2.0 mm yr^{-1} in the Pacific. Results show that 86% of islands remained stable (43%) or increased in area (43%) over the timeframe of analysis. Largest decadal rates of increase in island area range between 0.1 to 5.6 ha. Only 14% of study islands exhibited a net reduction in island area. Despite small net changes in area, islands exhibited larger gross changes. This was expressed as changes in the planform configuration and position of islands on reef platforms. Modes of island change included: ocean shoreline displacement toward the lagoon; lagoon shoreline progradation; and, extension of the ends of elongate islands. Collectively these adjustments represent net lagoonward migration of islands in 65% of cases. Results contradict existing paradigms of island response and have significant implications for the consideration of island stability under ongoing sea-level rise in the central Pacific. First, islands are geomorphologically persistent features on atoll reef platforms and can increase in island area despite sea-level change. Second; islands are dynamic landforms that undergo a range of physical adjustments in responses to changing boundary conditions, of which sea level is just one factor. Third, erosion of island shorelines must be reconsidered in the context of physical adjustments of the entire island shoreline as erosion may be balanced by progradation on other sectors of shorelines. Results indicate that the style and magnitude of geomorphic change will vary between islands. Therefore, island nations must place a high priority on resolving the precise styles and rates of change that will occur over the next century and reconsider the implications for adaption.

1. Introduction

Coral reef islands are low-lying accumulations of unconsolidated, or poorly lithified, carbonate sand and gravel deposited on coral reef platforms by the focussing effect of waves and currents (Stoddart and Steers, 1977). Coral reef islands are commonly found in barrier reef systems (e.g. Great Barrier Reef); open reef seas (e.g. Torres Strait) or in mid-ocean atolls. In atoll nations such as Tuvalu, Kiribati and the Maldives reef islands provide the only habitable area, which can carry very high population densities (e.g. 8300 people/km^2 on Fongafale, Tuvalu and 47,400 people/km^2 on Male, Maldives). These low-lying reef islands and their populations are considered physically vulnerable to a range of climate change impacts including: sea-level rise; changing weather and oceanographic wave regimes, and increased cyclone frequency and intensity (Church et al., 2006; Mimura et al., 2007). Under current scenarios of global climate-induced sea-level rise of 0.48 to 0.98 m by 2100 it is widely anticipated that low-lying reef islands will become physically unstable and be unable to support human populations over the coming century (Leatherman, 1997; Connell, 1999). The most anticipated physical impacts of sea-level rise on islands are shoreline erosion, inundation, flooding, salinity intrusion, and reduced resilience of coastal ecosystems (Leatherman, 1997; Mimura, 1999; Kahn et al., 2002; Yamano et al., 2007). It is also widely perceived that island erosion will become so widespread that entire atoll nations will disappear rendering their inhabitants among the first environmental refugees of climate change (Connell, 2004).

Attempts to resolve future island morphological response to global climate change can be divided into two broad groups. First a number of studies have examined the Holocene formation of islands as analogues of future response. Such studies have attempted to resolve critical linkages between reef growth, sea level and timing of island formation in order to project future morphological behaviour (e.g. Roy and Connell, 1991; Woodroffe and McLean, 1992, 1993; Dickinson, 1999; Kench et al., 2005, 2009a). Inevitably such assessments focus on

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the sea-level reef growth linkage as a critical boundary control of island adjustment but do not recognise that such adjustments typically occur at timescales at least an order of magnitude greater (centennial to millennial) than timescales relevant to island morphological adjustment in the near-future (Kench et al., 2009b). Second, a number of studies have relied on the extant geomorphic properties of islands to argue varying levels of resilience or resistance (Woodroffe and McLean, 1993). For example, Woodroffe (2008) noted that the susceptibility of islands to morphological change can be expected to vary considerably depending on subtle differences in island topography and geomorphic characteristics such as reef elevation and whether island material is partially lithified. Typically, these studies treat islands as static landforms. In particular, studies of future flooding and inundation have made projections of future flood risk based on static landform boundaries (Mimura, 1999; Kahn et al., Q5 2002; Yamano et al., 2007).

Collectively, these approaches provide insights into the past development and existing morphological attributes of reef islands with which to infer potential morphological adjustment or resilience. However, such approaches have not incorporated a full appreciation of the contemporary morphodynamics of landforms nor considered the style and magnitude of changes that may be expected in the future. Reef islands are dynamic landforms that are able to reorganise their sediment reservoir in response to changing boundary conditions (wind, waves and sea-level, Kench et al., 2009b). An increasing number of studies have shown that reef islands exhibit a high degree of morphological variability with respect to location and planform configuration on reef surfaces, in response to changing wind and wave patterns (Flood, 1986; Kench and Brander, 2006). Extreme events (cyclones and tsunami) have also been shown to have promoted both island erosion (Stoddart, 1963, 1971; Flood and Jell, 1977; Harmelin-Vivien, 1994) and accretion signatures (Maragos et al., 1973; Webb, 2006; Kench et al., 2006) depending on the calibre of sediment comprising islands and whether islands are located in storm or non-storm environments (Bayliss-Smith, 1988). Of note, these studies have shown differing modes of island shoreline adjustment that include horizontal displacement, and washover sedimentation that can vertically build island surfaces (e.g. Kench and Cowell, 2001; Kench et al., 2006, 2009b).

At inter-annual to decadal timescales studies have also identified changes in island size and position on reefs (Taylor, 1924; Stoddart et al., 1978; Flood, 1986; Aston, 1995). Umbgrove (1947) and Verstappen (1954) were the first to develop a causal relationship between climate and reef island behaviour invoking medium-term (decadal) shifts in prevailing wind direction and strength and its influence on wave energy as a control on morphological adjustment of islands in Djakarta Bay, Indonesia. Flood (1986) also related decadal changes in wind to progressive shifts in reef island planform in the Great Barrier Reef whereas, Stoddart et al. (1982) found that decadal change on islands within the Belize barrier reef system resulted from hurricane activity. There are a number of conspicuous features of these medium-term studies that are relevant to the issue of future island change. First, they have focused either on islands in fringing or barrier reef settings. Studies of atoll island change are scarce (Kench and Harvey, 2003). Second, these decadal-scale studies have generally linked island morphological change to shifts in climate (wind). Third, short and medium-term analogues of morphological change have not been adopted to project near-future changes in reef islands, despite the fact that climate has been implicated as the driver of morphological change. Fourth, these studies generally occurred prior to concerns over accelerated sea-level rise and no contemporary study exists that has attempted to examine decadal-scale island adjustments in response to variations in sea level.

In contrast to studies of physical island change, there has been considerable scientific effort in reconstructing past and present sea-level behaviour. The global dataset on sea-level trends over the past 130 yr shows an increase in global averaged mean sea level of approximately 200 mm (Fig. 1A). Analysis of available sea-level data from the northeast, central and western Pacific show significant regional differences in sea-level behaviour over the past century but generally agree with the large-scale global trend (Fig. 1B). However, numerous studies have noted the lack of long-term sea-level records from the Pacific Ocean, with this region being under-represented in analyses of global sea-level change (Milne et al., 2009). Over the past 20 yr there has been an increase in the number of high quality water level gauges deployed in islands in the southwest and central Pacific (South Pacific Sea Level and Climate Monitoring Project), with which to resolve high resolution sea-level behaviour (Church et al., 2006; Q6 Fig. 2). Furthermore, satellite altimeter data (TOPEX/Poseidon and Jason-1) captured over the past 17 yr has provided near-global maps of absolute sea level generated at 10-day intervals and has permitted sea-level trends to be identified for the world's oceans (Milne et al., 2009).

Current consensus of regional sea-level patterns in the central and southwest Pacific over the past 50 to 100 yr indicates sea level is subject to large inter-annual variations of ±0.45 m driven by ENSO cycles (Church et al., 2006). Superimposed on these short-term oscillations is a long-term trend of sea-level rise on the order of 1.6 mm yr^{-1}, which is Q7, Q8 consistent with global projections (Church et al., 2006; Milne et al., 2009; Woodworth et al., 2009). However, data also show considerable

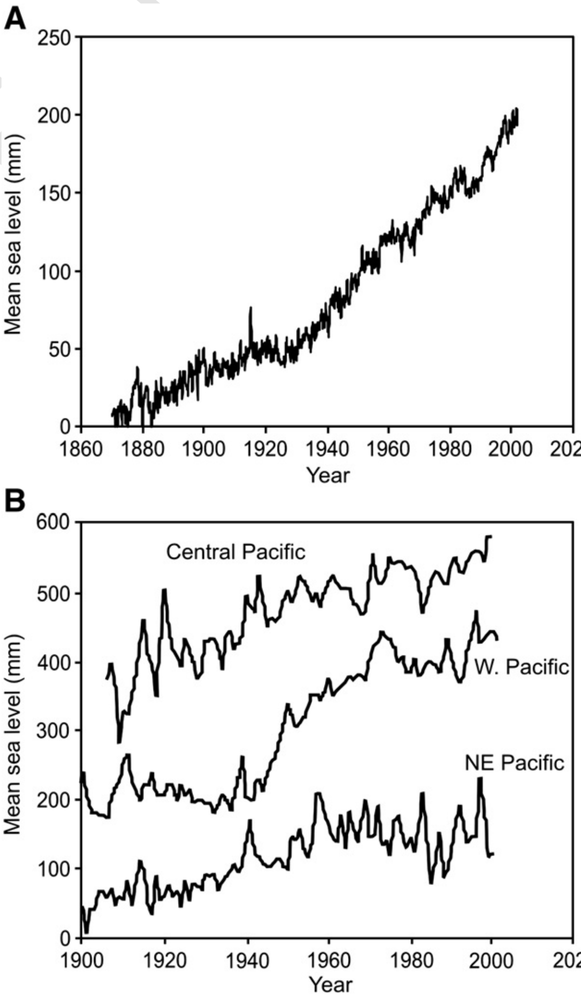

Fig. 1. A) The monthly global mean sea level time series derived from tide-gauge data 1870–2002, source data (Church and White, 2006). Sea level was reconstructed as described in Church et al., 2004. B) Sea level curves derived from tide-gauge data using the 'virtual station' method. Each time series has been offset along the y axis by an arbitrary amount to avoid overlap (from Milne et al., 2009).

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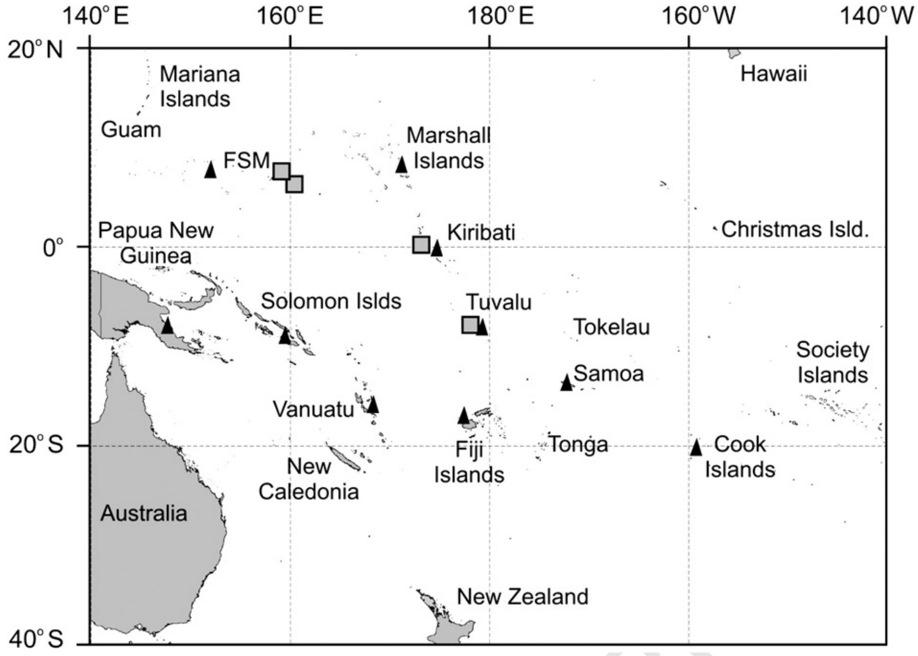

Fig. 2. Location diagram of the southwest Pacific Ocean showing network of seaframe water level gauges (triangles) and atolls in this study (grey boxes).

within region variation. Most records show an increase over a 50 yr time horizon ranging from 0.5 mm yr^{-1} at Malakal, Palau to 2.1 mm yr^{-1} at Majuro atoll, Marshall Islands (Church et al., 2004). Of note, sea-level rise at Majuro and Funafuti in the central Pacific is 2.1 and 1.6 mm yr^{-1} respectively although there is considerable uncertainty in the records on the order of ±0.3 mm yr^{-1}. In addition there is tentative evidence that sea-level rise is accelerating throughout the tropical Indian and Pacific Oceans (Church and White, 2006; Woodworth et al., 2009).

Despite assertions of island vulnerability to sea level and climatic change there have been few studies that have quantified island morphological change at the same temporal scale as detailed sea level records. Indeed, no systematic monitoring programme exists to document detailed reef island morphological change (Kench and Harvey, 2003). The lack of monitoring seems a gross oversight given the international concern over small island stability and pressing concerns of island communities to manage island landscapes. Furthermore, the lack of island shoreline monitoring represents a missed opportunity to couple morphological change data with the detailed sea-level records that have been accruing over the past 18 yr (Kench and Harvey, 2003).

This study presents new data on decadal-scale atoll island landform dynamics in the central Pacific Ocean. It addresses the question whether atoll islands have shown any consistent trends in morphological stability as a consequence of documented increases in sea level over the past half century. Specific objectives are to evaluate the net changes in reef island planform configuration over the past 20–60 yr, and examine gross changes in island planform adjustment over decadal timeframes. Significantly, the temporal scale of analysis overlaps the period in which sea level records have been analysed to establish rates of sea level change on the order of 2.0 mm yr^{-1} in the central Pacific Ocean. Consequently, our results are used to evaluate assumptions that increased sea level will destabilise and cause net erosion of atoll islands.

2. Field setting

This study examines the planform morphological change of 27 atoll islands located in the central Pacific (Figs. 2 and 3). The islands are located in three Pacific countries, in four atolls, and span 15° of latitude from Mokil atoll in the north (6°41.04′ N) to Funafuti in the South (8°30.59′S). The atolls vary significantly in terms of size, structure and number of islands distributed on the atoll rim. The atolls also vary in potential exposure to tropical cyclones. Whereas the Federated States of Micronesia (FSM) and Tuvalu can be affected by cyclones, equatorial Kiribati has no record of direct cyclone impact. All 27 islands in the study are located on atoll reef rims of Holocene age. Therefore, the islands are all also of Holocene age (McLean and Hosking, 1991; Dickinson, 1999).

Two atolls were examined from the Federated States of Micronesia (Fig. 3C and D). Mokil and Pingelap atolls are both small with a total area of approximately 8 and 12 km^2 respectively and with continuous atoll reef rims that enclose a central lagoon. Both atolls have three islands on their reef platforms found on all exposures of the atoll rim. The islands are of varying size and shape with the longest axes ranging from 0.42 to 3.54 km and width ranging from 0.18 to 0.48 km (Table 1).

Tarawa atoll in the Republic of Kiribati (1° 26.2′ N and 172° 58.8′ E) is broadly triangular in shape with dimensions of approximately 40 km in length and 25 km in maximum width (Fig. 3B). An open submerged reef system characterises the western atoll rim with a single deeper passage connecting the lagoon and open ocean. Islands form a near-continuous chain along the eastern and southern sections of the atoll reef rim (Fig. 3B). This study examined four islands in Tarawa atoll; three islands from South Tarawa and the most northern island Buariki (Fig. 3B). These islands differ significantly in energy exposure, size and level of development. The three islands located on the southern atoll rim are all inhabited and are part of the urban precinct South Tarawa. Nanikai is the smallest island measuring 0.82 km in length and only 0.11 km in width (total area of 6.4 ha). In contrast Betio measures 4.4 km in length and 0.36 km in mean width (area of 120 ha). These islands have a range of structures on the ocean and lagoon shorelines. The largest island studied is located in North Tarawa. Buariki has a dimension of 6.6 km in length and up to 0.54 km in width (area of 338 ha, Table 1).

Funafuti atoll in Tuvalu (8° 30.6′ S and 179° 6.9′ E) measures approximately 20 km in length and up to 15 km in width (Fig. 3A). The atoll has a near-continuous reef rim that surrounds the lagoon, with a small number of deep passages that connect the lagoon to open ocean. There are only a few small islands on the western leeward reef rim (Fig. 3A). Islands are present on the northeast to southern sections of the atoll reef rim. Eighteen islands spanning the northern to southern extent of the atoll were selected for analysis (Table 1). The

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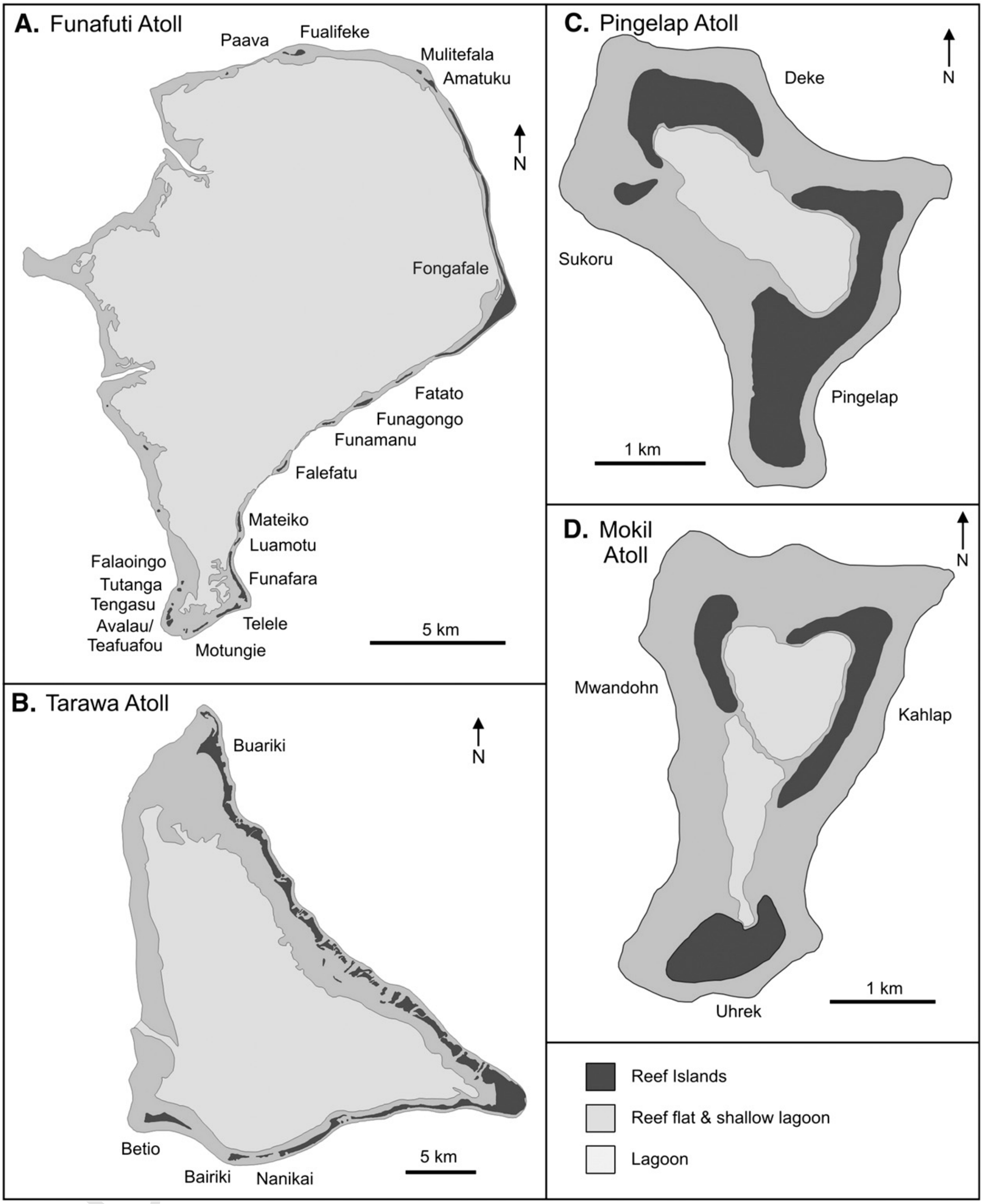

Fig. 3. Location of study islands in four atolls selected for analysis. Islands examined in this study are labelled.

islands vary significantly in dimension and overall size. Tengasu in the southwest of the atoll is the smallest island with dimensions of 0.07 × 0.08 km in length and width with a total area of 0.68 ha. Funafara in the southeast of the atoll has dimensions of 2.2 km (length) and 0.11 km (width) with an area of 22.9 ha.

Sea level records from the nearest sea level recorder to each atoll are presented in Fig. 4 for the past 20 to 30 yr. These records show large inter-annual variations and are in general agreement with regional patterns and rates of sea level rise, in the order of 2.0 mm yr^{-1}. Consequently, the study islands have all experienced increase in sea level over the past 20 yr.

3. Methodology

A total of 27 islands were examined using comparative analysis of historical aerial photography and remotely sensed images. Historical aerial photographs were either scanned from hard copies or negatives at minimum resolution of 900 dpi. The aerial photographs used all had

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Table 1
Physical attributes of study islands and timespan of aerial imagery.

Atoll / Island	Coordinates		Atoll rim location	Island physical characteristics			Time span of imagery (yr)
	Latitude	Longitude		Length (km)	Width (km)	Area (ha)	
Funafuti Atoll	8° 30.592′ S	179° 6.932′ E					
Paava Island	8° 25.651′ S	179° 7.002′ E	North	0.24	0.08	1.48	1984–2003
Fualifeke Island	8° 25.649′ S	179° 7.350′ E	North	0.50	0.17	6.85	1984–2003
Mulitefala Island	8° 26.062′ S	179° 10.016′ E	Northeast	0.75	0.11	2.33	1984–2003
Amatuku[b]	8° 26.301′ S	179° 10.277′ E	Northeast	0.70	0.11	6.13	1984–2003
Fatato	8° 32.865′ S	179° 9.732′ E	Southeast	0.85	0.07	5.11	1984–2003
Funagongo	8° 33.478′ S	179° 8.778′ E	Southeast	1.11	0.13	10.66	1984–2003
Funamanu	8° 33.918′ S	179° 8.012′ E	Southeast	0.55	0.08	2.99	1984–2003
Falefatu	8° 34.904′ S	179° 6.980′ E	Southeast	0.62	0.06	3.23	1984–2003
Mateiko	8° 36.133′ S	179° 6.006′ E	Southeast	0.81	0.08	4.25	1984–2003
Luamotu	8° 36.562′ S	179° 5.948′ E	Southeast	0.43	0.05	1.80	1984–2003
Funafara	8° 37.451′ S	179° 5.961′ E	Southeast	2.2	0.11	22.95	1984–2003
Telele	8° 38.131′ S	179° 5.731′ E	South	1.34	0.05	8.83	1984–2003
Motungie	8° 38.503′ S	179° 5.155′ E	South	0.86	0.05	4.97	1984–2003
Avalau/Teafuafou	8° 38.277′ S	179° 4.463′ E	Southwest	0.71	0.16	12.14	1984–2003
Tengasu	8° 37.983′ S	179° 4.547′ E	Southwest	0.07	0.08	0.68	1984–2003
Tutanga	8° 37.651′ S	179° 4.689′ E	Southwest	0.13	0.15	1.66	1984–2003
Falaoingo	8° 37.504′ S	179° 4.749′ E	Southwest	0.17	0.06	1.31	1984–2003
Tarawa Atoll	1° 26.178′ N	172° 58.779′ E					
Betio[a]	1° 21.356′ N	172° 55.901′ E	Southwest	4.4	0.36	120.03	1943–2004
Bairiki[a]	1° 19.773′ N	172° 58.674′ E	South	1.78	0.28	35.46	1969–2004
Nanikai[a]	1° 19.814′ N	172° 59.851′ E	South	0.82	0.11	6.40	1969–2004
Buariki[b]	1° 36.634′ N	172° 57.787′ E	Northeast	6.58	0.54	338.30	1943–2004
Pingelap Atoll	6° 13.031′ N	160° 42.169′ E					
Deke	6° 13.672′ N	160° 41.824′ E	North	1.31	0.40	59.90	1944–2006
Sukoru	6° 13.217′ N	160° 41.575′ E	West	0.21	0.42	5.84	1944–2006
Pingelap[b]	6° 12.439′ N	160° 42.348′ E	East	3.54	0.48	127.00	1944–2006
Mokil Atoll	6° 41.044′ N	159° 45.476′ E					
Mwandohn	6° 41.496′ N	159° 45.155′ E	West	1.11	0.24	26.19	1944–2006
Kahlap[b]	6° 41.192′ N	159° 45.891′ E	East	2.97	0.18	55.90	1944–2006
Uhrek	6° 39.044′ N	159° 45.476′ E	South	1.19	0.48	51.50	1944–2006

Island length is the longest axis of the island parallel to the reef rim.
Island width represents the mean width of the island perpendicular to the reef rim.
Island area calculated from the earliest aerial imagery.

[a] Denote densely populated and urbanised islands.

[b] Denote islands with small rural villages.

a scale of <1:25,000. Once scanned these images were enhanced to maximise contrast of features, orientated to grid North and in some cases cropped to avoid excessive overlap.

The timeframe of analysis is different between atolls and islands depending on aerial photograph coverage and availability (Table 1). The minimum time period is 19 yr for islands in Funafuti with the maximum timespan of 61 yr for Mokil and Pingelap. Georectification and referencing of the historical aerial photographs was accomplished using ERDAS Imagine 8.4 software using georeferenced (UTM WGS 84) IKONOS and/or Quickbird satellite imagery as the source of ground control points. Once corrected the historical images were saved as geotif image files with WGS 84 co-ordinate system embedded. Truthing of each image was achieved by comparison of reliable ground control points between the georeferenced satellite images and the georectified historical images (Thieler and Danforth, 1994; Graham and Koh, 2003). Each historical image was subsequently re-corrected using the same process until error between the satellite and historical images was due to issues of resolution rather than systematic error in position of control points (Moore, 2000).

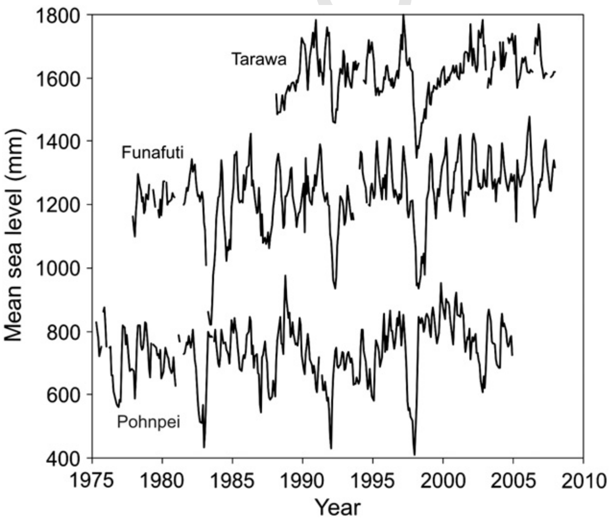

Fig. 4. Historical sea level observations for study atolls Tarawa and Funafuti and nearest record for Pingelap and Mokil (Pohnpei, Federated States of Micronesia).

Due to the isolated and undeveloped nature of many of these islands there were considerable challenges in identifying conventional permanent reference points (such as surveyed datum points) which can be commonly found in images from differing time periods (Thieler and Danforth, 1994). Additionally, features such as sealed roads and permanent buildings are often restricted to only small areas on any particular island and are almost absent in the pre 1960's historical images. Consequently, a range of anthropogenic (e.g. ancient stone fish traps) and natural geomorphic features that have temporal stability (e.g. beach rock and conglomerate outcrops) were used for rectification.

A further limitation in the analysis of aerial photographs is the differing resolution or quality of images (Anders and Byrnes, 1991). Aerial photographs generally have better resolution than satellite images but older air photos may be similarly limited due to the state of technology at that time and/or the poor condition of negatives. It should also be recognised that historical images were seldom acquired with the specific intention of use as a coastal management tool and as such, the

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flight angles and paths, exposure, coverage and elevation are often not optimum. Nevertheless, these photographic records when compared as a time series, offer the best opportunity available to determine accurate rates and patterns of coastal change and processes over time.

Georectification and analysis is reliant on an intimate knowledge of land, shoreline and shallow marine forms and structures in these atoll environments. Ground-truthing and community discussion of the changes perceived from this work was also undertaken between 2004 and 2006 and there was consistent agreement with the findings of the study. Error is largely determined by the resolution of satellite imagery (Funafuti – 4 m IKONOS and Tarawa, Pingelap and Mokil – 0.6 m Quickbird; Crowell et al., 1991). Due to the accuracies of aerial photographs measured changes in shoreline position within ±3% were not considered significant and reflect relative stability of islands.

Once images were rectified analysis involved the overlay of the historical time series for each island. Areas of accretion and erosion were subsequently identified. Changes in island area were calculated and compared to establish change through time. Observations of changes in the configuration and position of the island on the reef platforms were also made.

4. Results

Summary data on changes in island area are presented in Table 2 and selected examples of changes in the planform configuration of islands over the time interval of analysis are shown in Figs. 5–8.

On Funafuti islands exhibited differing physical adjustments over the 19 yr of analysis. Six of the islands have undergone little change in area (<±3%). Seven islands have increased in area by more than 3%. Maximum increases have occurred on Funamanu (28.2%), Falefatu (13.3%) and Paava (10.1%). In contrast, four islands decreased in area by more than 3%. The largest decrease in area is in Tengasu (−14.7%) although it should be noted that this was the smallest island examined. The remaining three islands all decreased in area by less than 4% in area.

Plannimetric changes are illustrated for selected islands in Fig. 5. Notable planform adjustments include: expansion (progradation) of lagoon shorelines on Fualifeke, Mulitefala and Funamanu; extension of the ends of the elongate island Funamanu; and erosion of ocean shorelines on a number of islands (Fig. 5; Table 2). As illustrated by Mulitefala, erosion of the ocean shoreline and expansion of lagoon shorelines results in net displacement of the island in a lagoonward direction across the reef. However, on the leeward reef, islands exhibit lagoonal erosion and either expansion or stability of oceanside coastlines (e.g. Falaoingo and Tutanga, Fig. 5E).

Analysis of island change over a 35–61 yr timeframe on Tarawa atoll shows that all four islands exhibited an increase in island area. Notably the three urbanised islands of Betio, Bairiki and Nanikai increased in area by 30, 16.3 and 12.5% respectively. Buariki in the north of the atoll exhibited an increase of 2%. This was the largest island examined and represents an increase in area of 10.1 ha (Table 2).

Changes in the planform configuration of Betio and Bairiki show an expansion in the island footprint on both ocean and lagoon shorelines (Fig. 6E and D). Nanikai displays oceanside erosion, embayment infilling and eastward extension by up to 300 m (Fig. 6C). Buariki exhibited localised embayment infilling on the exposed ocean shoreline and

Table 2
Summary of island change characteristics.

Atoll/island	Time period (Yr)	Initial area (Ha)	Final area (Ha)	Net island change		Decadal rate of change		Geomorphic change in island planform characteristics		
				(Ha)	(%)	(Ha)	(%)	Ocean shore	Lagoon shore	Dominant style of island planform adjustment
Funafuti Atoll										
Paava Island	19	1.48	1.63	0.15	10.0	0.08	5.26	Accretion	Erosion	Ocean migration and contraction of eastern end of island
Fualifeke Island	19	6.85	6.61	−0.24	−3.5	−0.13	−1.84	Erosion	Accretion	Lagoon migration of N and E shorelines. Island tip extension
Mulitefala Island	19	2.33	2.35	0.02	0.8	0.01	0.42	Erosion	Accretion	Lagoon migration. Contraction NW end of island
Amatuku[b]	19	6.13	6.42	0.29	4.6	0.15	2.42	Accretion	Accretion	Island expansion, lagoon progradation. Contraction NW end of island
Fatato	19	5.11	5.54	0.44	8.6	0.23	4.53	Accretion	Accretion	Lagoon migration N end. Extension of S and N ends of island
Funagongo	19	10.66	10.76	0.10	1.0	0.06	0.53	Erosion	Accretion	Lagoon migration NE end
Funamanu	19	2.99	3.83	0.84	28.2	0.44	14.84	Stable	Stable	Lagoon migration, extension of W and E ends of island
Falefatu	19	3.23	3.66	0.43	13.3	0.73	7.00	Erosion	Accretion	Lagoon migration. SW end stable, Lagoon migration central and N end
Mateiko	19	4.25	4.51	0.26	6.1	0.14	3.21	Erosion	Accretion	Lagoon migration
Luamotu	19	1.80	1.74	−0.06	−3.3	−0.03	−1.74	Erosion	Accretion	Lagoon migration. S end contracted, N end extension
Funafara	19	22.95	23.78	0.83	3.6	0.43	1.89	Accretion	Accretion	Lagoonward deposition in S, spit growth and embayment infilling
Telele	19	8.83	8.87	0.04	0.5	0.02	0.26	Erosion	Accretion	Lagoonward migration
Motungie	19	4.97	5.03	0.05	1.0	0.03	0.53	Erosion	Accretion	Lagoon migration. SW tip extension ~100 m.
Avalau/Teafuafou	19	12.14	11.89	−0.25	−2.1	−0.14	−1.11	Erosion	Erosion	Contraction. Localised embayment sedimentation
Tengasu	19	0.68	0.59	−0.10	−14.7	−0.05	−7.74	Stable	Erosion	Contraction of lagoon shoreline
Tutanga	19	1.66	1.60	−0.06	−3.6	−0.03	−1.89	Stable	Erosion	Contraction of lagoon shoreline
Falaoingo	19	1.31	1.31	0.00	0.0	0.00	0.00	Stable	Erosion	Contraction of lagoon shoreline
Tarawa Atoll										
Betio[a]	61	120.03	156.0	36.0	30.0	5.81	4.84	Accretion	Accretion	Expansion of island footprint, localised areas of erosion
Bairiki[a]	35	35.46	41.25	5.79	16.3	1.65	4.66	Accretion	Accretion	Expansion of island footprint, localised areas of erosion
Nanikai[a]	35	6.40	7.20	0.80	12.5	0.23	3.57	Accretion	Accretion	Lagoon expansion, embayment infilling
Buariki[b]	61	338.30	348.40	10.1	2.9	1.62	0.48	Accretion	Accretion	Lagoon expansion of cuspate shoreline. Embayment deposition
Pingelap Atoll										
Deke	62	59.90	60.61	0.70	1.2	0.11	0.19	Accretion	Erosion	General stability slight northward movement.
Sukoru	62	5.84	5.74	0.10	−1.7	−0.02	−0.27	Erosion	Accretion	Lagoonward migration. Spit extension into lagoon
Pingelap[b]	62	127.00	125.0	2.00	−1.2	−0.24	−0.19	Erosion	Stable	Accretion NW tip and north coast
Mokil Atoll										
Mwandohn	62	26.19	27.40	1.20	4.6	0.19	0.74	Stable	Accretion	Lagoonward expansion. Pronounced extension of N and S end of island
Kahlap[b]	62	55.90	57.80	1.90	1.6	0.15	0.26	Erosion	Accretion	Lagoonward migration. Extension of N and S end of island
Uhrek	62	51.50	52.90	1.40	2.7	0.23	0.44	Erosion	Accretion	Lagoonward migration. Movement of NE end, embayment infilling

[a] Denote densely populated and urbanised islands.
[b] Denote islands with small rural villages.

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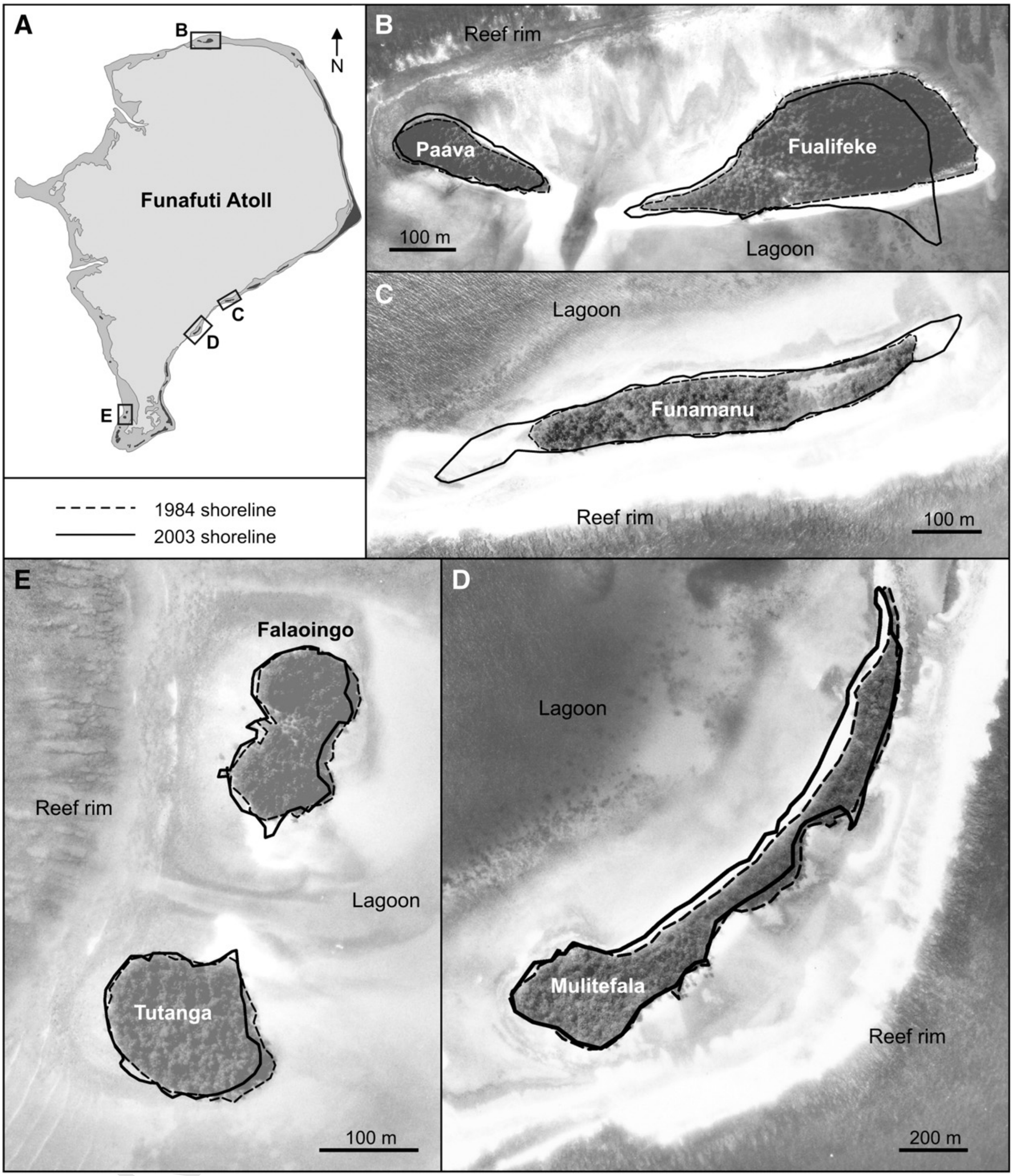

Fig. 5. Changes in reef island planform characteristics 1984–2003 for selected study islands Funafuti atoll, Tuvalu.

minor erosion/migration on the northern and western (lagoon) points. Localised accretion was detected on the lagoon shore (Fig. 6B).

The islands of Pingelap atoll have remained relatively stable over the 62 yr of analysis with changes in island area all less than 2% (Table 2, Fig. 7). There is evidence that the islands of Pingelap (main island) and Sukoru both exhibited erosion of the ocean shoreline and accretion of the lagoon coastline (Fig. 7C and D). In contrast, lagoon erosion and oceanside accretion is evident on Deke (Fig. 7B).

Over a similar 62 yr window of analysis the islands on Mokil also show a minor amount of change. However, in each case the change is an increase in island area from 1.6% on Kahlap to 4.6% on Mwandohn (Fig. 8B and C). While the percentages are small they represent the net addition of more than 1 ha of land on each island (Table 2). The islands show evidence of localised erosion of the ocean shoreline. Mwandohn and Uhrek both show lagoon accretion while Kahlap and Mwandohn also exhibit extension of the eastern and southern ends of islands respectively (Fig. 8C and B).

5. Discussion

Results show that all islands have undergone physical change over the respective timeframes of analysis and over the period in which the instrumental records indicate an increase in sea level. The data indicate that islands have undergone contrasting morphological

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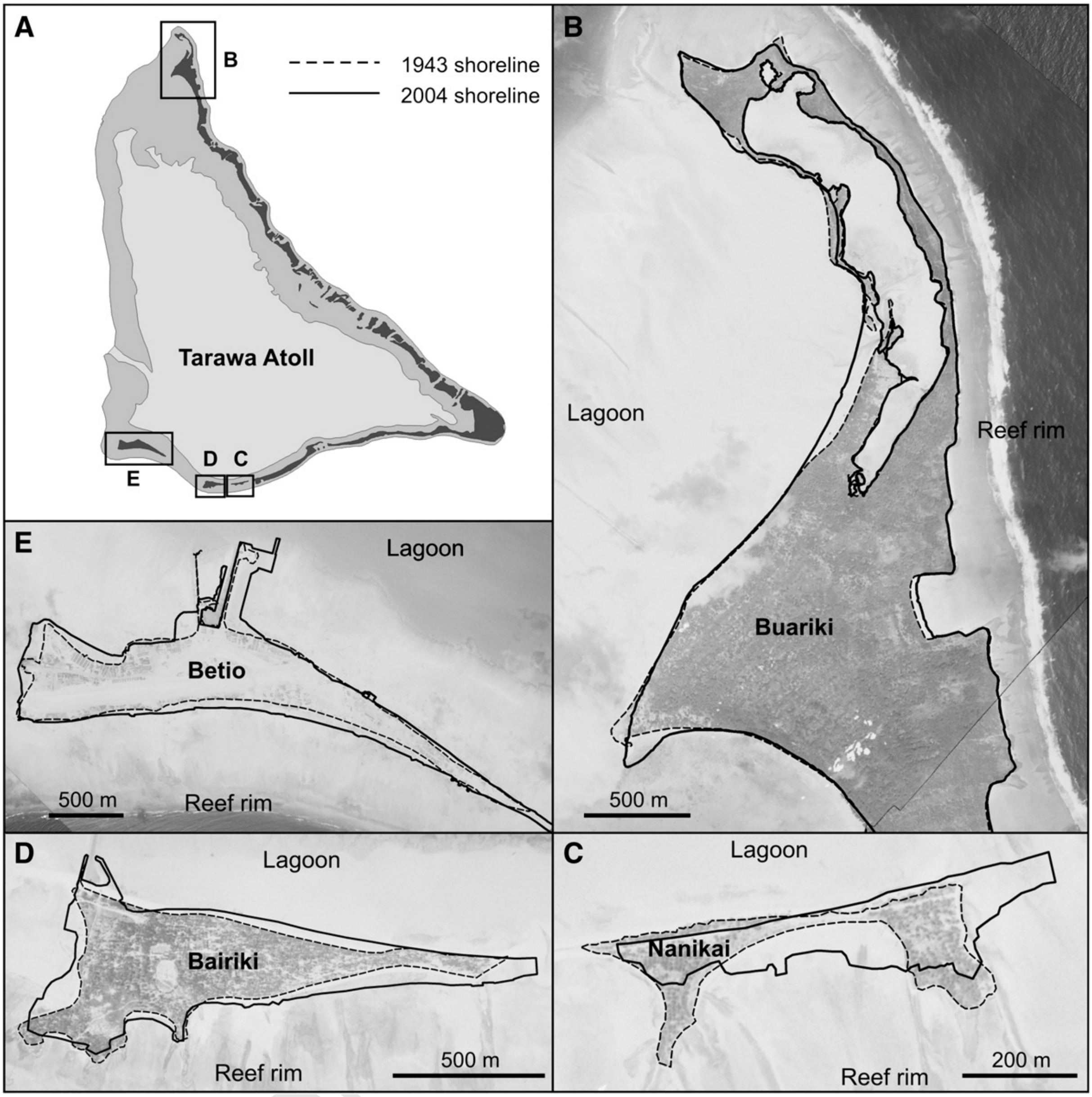

Fig. 6. Changes in reef island planform characteristics for selected study islands on Tarawa atoll, Kiribati. B) Buariki and E) Betio 1943–2004. C) Nanikai and D) Bairiki 1969–2004.

adjustments over the period of analysis. Furthermore, the magnitude and styles of island change show considerable variation both within and between atolls in the study.

5.1. Net change in island area

The total change in area of reef islands (aggregated for all islands in the study) is an increase in land area of 63 ha representing 7% of the total land area of all islands studied. The majority of islands appear to have either remained stable or increased in planform area (86%). Forty-three percent of islands have remained relatively stable (<±3% change) over the period of analysis. A further 43% of islands (12 in total) have increased in area by more than 3%. The remaining 15% of islands underwent net reduction in island area of more than 3%.

Of the islands that show a net increase in island area six have increased by more than 10% of their original planform area. Three of these islands were in Funafuti; Funamanu increased by 28.2%, Falefatu 13.3% and Paava Island by 10% (Table 2). The remaining three islands are in Tarawa atoll with Betio, Bairiki and Nanikai increasing by 30%, 16.3% and 12.5% respectively over the 60 yr period of analysis (Table 2). Of note, the large percentage change on Betio represents an increase of more than 36 ha.

There appears to be no relationship between island area and the direction and magnitude of island change (Fig. 9). Islands with increases of more than 10% in area are all greater than 1 ha, while the island with the largest increase (Betio) had an initial area of approximately 120 ha. Consequently the percentage increase represents a large absolute increase in land area.

Only one island has shown a net reduction in island area greater than 10%. Tengasu is located on the southwest atoll rim of Funafuti and decreased in area by 14% over the 19 yr period of analysis. However, closer examination of the Tengasu data shows that it was the smallest island in the study sample (0.68 ha) and the absolute change in island area was 0.1 ha, which represents a substantial proportion of the total island area. Of note, approximately 50% of islands exhibited changes in island area greater than 1.0 ha (Table 2).

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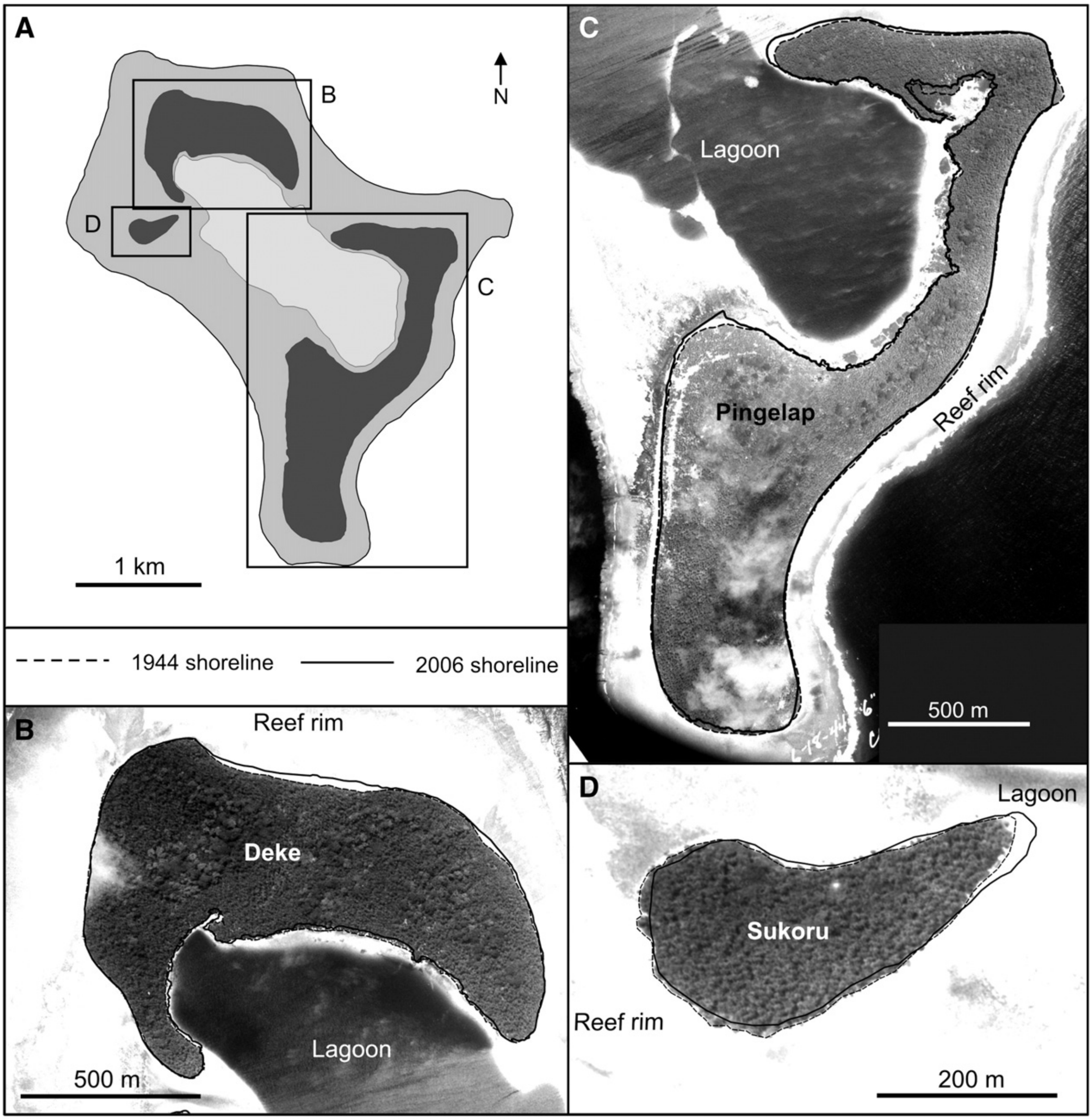

Fig. 7. Changes in reef island planform characteristics for selected study islands 1944–2006 on Pingelap atoll, Federated States of Micronesia.

5.2. Net vs gross island planform change

The net changes in island area mask larger gross changes in island planform configuration and location on the reef platform that have occurred over the time periods of analysis. For example, on Fualifeke in Funafuti (Fig. 5B), the eastern half of the island has migrated south indicating up to 30% of island materials have been reworked over the 19 yr window of analysis. In another example, on the island of Mulitefala (Funafuti, Fig. 5D) erosion on the oceanside of the island has been compensated by progradation on the lagoon shoreline.

5.3. Styles of island planform change

Examination of gross changes in island planform across the analysis period indicates that entire shorelines of islands may have undergone positional adjustment. When individual shoreline changes are aggregated to the island scale they represent adjustments in the nodal position of islands on their reef surfaces. A number of styles of island planform adjustment are evident and are summarised in Table 3.

5.3.1. Ocean shoreline adjustments

Erosion of shorelines facing the ocean reef was detected in 50% of islands examined. While in most cases this represented marginal trimming of the island shoreline (often localised) in some cases it produced up to 5–10 m of shoreline displacement. In the majority of examples ocean shoreline erosion occurred on islands on the windward margin of the atoll, which receives maximum oceanic swell energy. Accretion of ocean shorelines was apparent on 30% of islands examined. In nearly every instance such accretion occurred on the leeward (non-exposed) margins of the atoll (e.g. Paava in Funafuti, Fig. 5B; Deke in Pingelap, Fig. 7B).

5.3.2. Lagoon shoreline adjustments

Accretion of lagoon shorelines was detected in 70% of the islands examined (Table 3). While accretion was generally on the order of 5–

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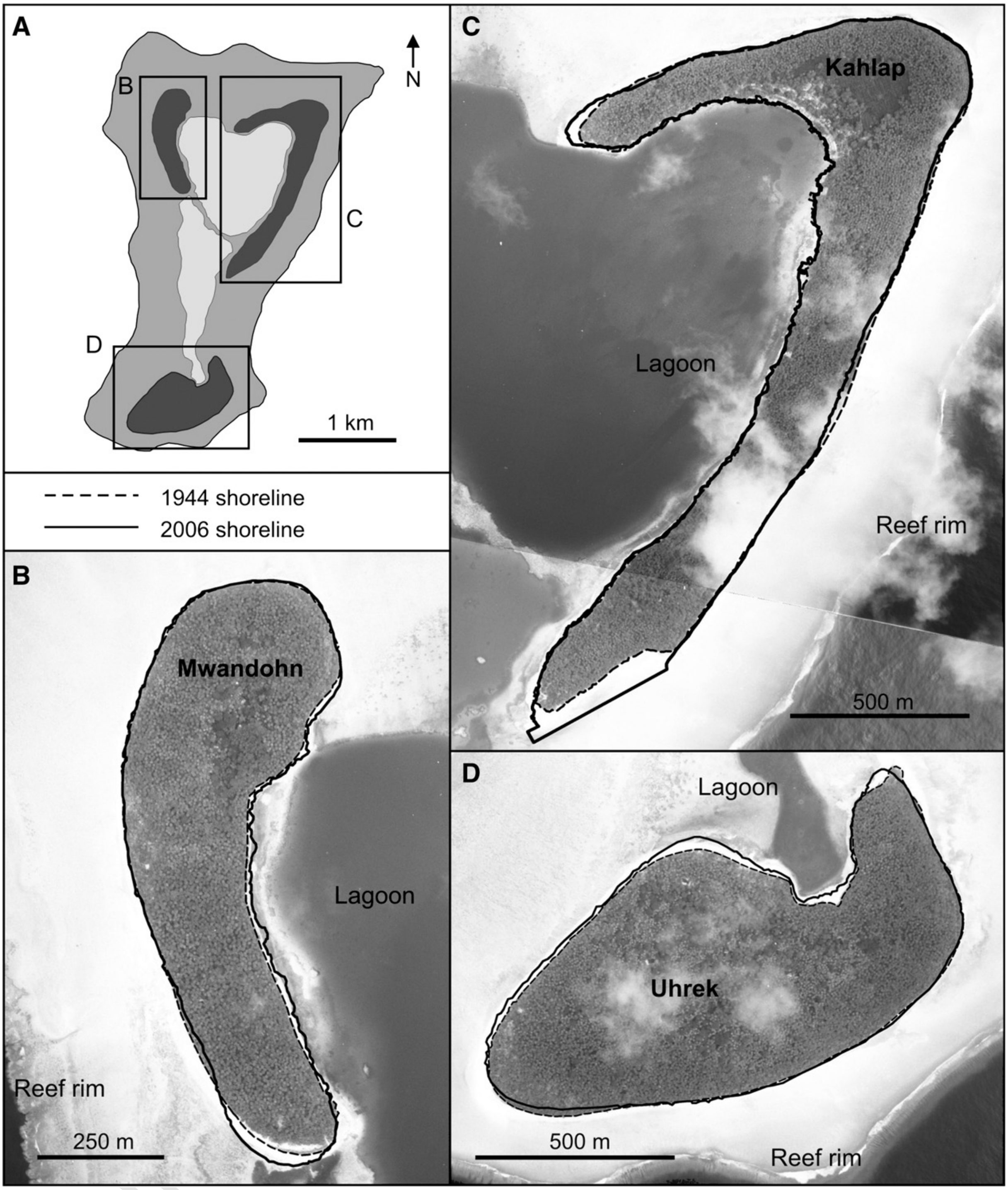

Fig. 8. Changes in reef island planform characteristics for selected study islands 1944–2006 on Mokil atoll, Federated States of Micronesia.

10 m in some cases maximum lagoonward accretion was on the order of 20–40 m (e.g. Fualifeke and Mulitefala, Fig. 5B and D; all islands in Tarawa, Fig. 6).

5.3.3. Island migration

The aggregated effect of ocean shoreline displacement and lagoon progradation is a shift in the nodal position of islands on reef surfaces. Such movement, while small in magnitude, represents net lagoonward migration of islands and was observed in 65% of islands studied. This response is most evident on the windward margins of the atolls. In only one case was an island found to have migrated toward the reef edge (Paava, Funafuti, Fig. 5B). In this case the island was located on the leeward reef rim of the atoll.

5.3.4. Contraction, expansion and extension

Table 3 identifies a number of other styles of island adjustment which was observed in only a small number of islands. The extension of the ends of elongate islands was observed in a number of islands (~33%). This is most clearly observed on Funamanu in which gravel spits extended more than 100 m in 19 yr (Funafuti, Fig. 5C). A small number of islands also exhibited expansion (accretion on all shorelines) and contraction (erosion on all shorelines) in island area.

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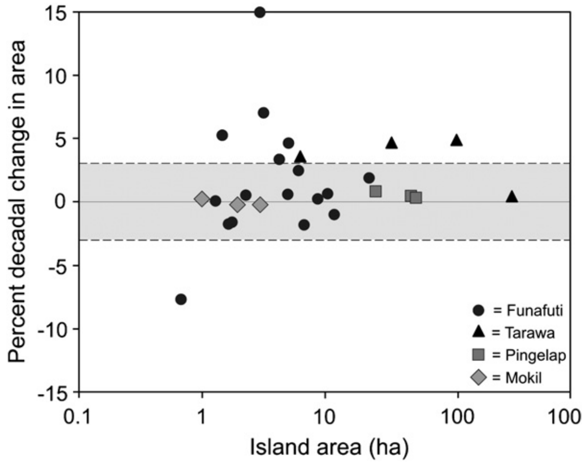

Fig. 9. Relationship between decadal change in reef islands (%) and reef island area for study islands.

5.4. Mechanisms driving change

There are a number of mechanisms that may account for the observed changes in atoll island planform configuration.

5.4.1. Change in boundary conditions: sea level and climate

Sea level rise has been implicated as a primary mechanism that may promote erosion and complete destabilisation and loss of islands in atoll environments (Dickinson, 1999; Barnett and Adger, 2003; Kahn et al., 2002). Such assertions invoke sea level as the primary control on island stability and persistence. In this model increased sea level is expected to raise mean water depths across reef surfaces allowing higher wave energy to propagate onto reef surfaces, impacting and eroding island shorelines (Sheppard et al., 2005). The projected morphological response is erosion of the ocean shoreline. Such an adjustment assumes that atoll island shorelines are positioned at an equilibrium distance across the reef flat surface which reflects co-adjustment between relative water depth over the reef, incident wave energy, reef width and sediment calibre (Kench and Cowell, 2001; Kench et al., 2009b).

Results of this study show that a significant number of islands exhibit ocean shoreline erosion (50%, Tables 2 and 3) which may reflect shore readjustment to measured increased sea levels over the study period (Fig. 4) and potentially increased wave energy incident at shorelines. However, it is important to stress that such movement does not necessarily result in a net reduction in island area. While ocean shoreline erosion was prevalent (50% of islands) most islands (86%) displayed either no change in area or an increase in area. These observations suggest that in cases where there was no significant change in island area, shoreline erosion and lagoon progradation was balanced via reworking of the finite reservoir of sediment contained within islands. In cases with significant increase in area, ocean shoreline erosion is likely to have been compensated by larger lagoon progradation, which must have occurred through additional inputs of sediment to the island system. In both instances the islands migrated lagoonward on their reef platforms. These observations are consistent with those of Stoddart et al. (1982) who suggested that reef islands in Belize also displayed lagoonward migration in response to rising sea level.

Similar migration of islands on reef surfaces has been identified by Verstappen (1954) in the Indonesian seas and Flood (1986) in the Great Barrier Reef. In these examples, decadal-scale changes in prevailing wind systems and their influence on wave propagation (direction and energy) have been implicated in island migration. Indeed, Solomon and Forbes (1999) implicate inter-annual El-Nino Southern Oscillation variations and their control on the wind and wave regime as a control on erosion and accretion patterns in Kiribati. Kench and Brander (2006) also identified rapid morphological adjustment of reef island shorelines, and consequently island location on reef platforms in the Maldives in response to monsoonal variations in incident wind and wave energy.

Storms and hurricanes have also been shown to have both constructional and erosional impacts on reef sedimentary landforms with the contrasting responses reflecting differences in storm frequency and texture of island building materials (Bayliss-Smith, 1988). In settings with low storm frequency, landforms are typically composed of sand-size sediments, which are susceptible to erosion during extreme events (Stoddart, 1963). However, in reef settings with high storm frequency, islands are commonly composed of rubble on their exposed margins. In such settings, large volumes of rubble can be generated in single events from coral communities on the outer reef and contribute to island accretion (Chivas et al., 1986; Hayne and Chappell, 2001). In Tuvalu, Hurricane Bebe in 1972 deposited an extensive storm rubble rampart onto the reef flat of Funafuti atoll (Maragos et al., 1973). Subsequent storms have reworked this rampart onto island shorelines (as described by Baines and McLean, 1976) accounting for the increases in island area along the eastern reef rim of Funafuti (Table 2; Fig. 5). In particular, extension of the ends of the elongate islands is a consequence of onshore and alongshore transport of sediment (Fig. 5C).

5.4.2. Anthropogenic modification

As identified in Table 2 a number of the study islands contain human settlements. Those islands with small villages have exhibited small variations in island area. However, the most densely settled islands in the study are located in South Tarawa (Betio, Bairiki and Nanikai). These islands have all experienced an increase in island area greater than 10% over the period of analysis with a decadal rate of increase of between 3.5 and 4.8%. Indeed Betio increased in area by 30% (36 ha) and Bairiki by 16.3% (5.8 ha). This expansion in island area has occurred over a time period in which the shoreline has undergone significant modification and change in coastal processes. The shoreline has numerous coastal structures including seawalls, groynes and minor reclamations that all promote disruption to coastal processes. Causeways have also been inserted between islands along the southern atoll rim. The causeways block ocean to lagoon fluxes of water and sediment. Consequently, nearshore current and littoral drift processes have been altered promoting extension of the shoreline along causeways and increasing island area. Anthropogenic modification of coral reefs and island shorelines have been identified in a number of studies and are generally associated with negative environmental outcomes with regard reef health and shoreline erosion (Brown and Dunne, 1988; Maragos, 1993;

Table 3
Summary of physical adjustments of reef island shorelines.

Atoll	Shoreline adjustment						Island adjustment		
[No. of islands]	Ocean erosion	Ocean accretion	Lagoon erosion	Lagoon accretion	Spit extension	Contraction	Expansion	Lagoon migration	Ocean migration
Funafuti [17]	9	4	5	11	3	4	–	12	1
Tarawa [4]	–	4	–	4	3	–	4	–	–
Mokil [3]	2	–	–	3	1	–	–	3	–
Pingelap [3]	2	1	1	1	2	–	–	2	–
Total	13	9	6	19	9	4	4	17	1

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Sheppard et al., 2005). However, results presented in this study show that anthropogenically modified shoreline processes can also contribute to land building in atoll environments.

5.5. Implications for vulnerability assessments

The findings challenge the conventional frame of reference for considering shoreline adjustment in small reef island settings and for approaches to evaluate vulnerability. Typically assessments of shoreline change adopt 2-dimensional across-shore methods that are applied to single locations on island shorelines. In particular, the Bruun Rule is commonly advocated as an appropriate tool to assess coastal change (UNEP). This simple geometric profile model implies coastlines will migrate landward due to erosion and the relative extent of erosion is a direct function of the magnitude of sea-level rise and gradient of the coast. Whilst numerous studies have critiqued the use of this model for predicting shoreline change in response to sea level rise on sandy shorelines (e.g. Cooper and Pilkey, 2004) its continued use and advocacy at an international level is perplexing and ultimately misleading.

The physical characteristics of reef island coastlines confound the assumptions of the Bruun rule and render any results highly questionable (Cowell and Kench, 2001). First, reef islands are typically low in elevation and experience wave overtopping during storms and high energy wave events. Second, the presence of horizontal and non-erodable reef flat surfaces truncates the active beach. Third, atoll island shorelines have a 360° perimeter rather than a linear planform configuration as is common in siliciclastic settings. Consequently, alongshore sediment transport processes dominate shoreline change. Results presented in this study show that the entire footprint of islands are able to change so that erosion at the local scale (on one aspect of an island) may be offset by accretion on other parts of the coastline. This change was recognised by Kench and Brander (2006) who suggested that the 'sweepzone' (that demarcates the envelope of coastal change) on reef islands occurs through alongshore reorganisation of sediment as opposed to the across-shore exchange of sediment that characterises siliciclastic shorelines. Recognition of the alongshore adjustment of island shorelines suggests that local scale analysis of two dimensional shoreline adjustment using tools such as the Bruun Rule are subject to significant error when upscaled to the island scale. Consequently, assessments of island change must be evaluated at the 'whole island' scale involving analysis of potential change in the entire island perimeter.

6. Conclusions

The future persistence of low-lying reef islands has been the subject of considerable international concern and scientific debate. Current rates of sea level rise are widely believed to have destabilised islands promoting widespread erosion and threatening the existence of atoll nations. This study presents analysis of the physical change in 27 atoll islands located in the central Pacific Ocean over the past 20 to 60 yr, a period over which instrumental records indicate an increase in sea level of the order of 2.0 mm yr^{-1}.

The results show that island area has remained largely stable or increased over the timeframe of analysis. Forty-three percent of islands increased in area by more than 3% with the largest increases of 30% on Betio (Tarawa atoll) and 28.3% on Funamanu (Funafuti atoll). There is no evidence of large-scale reduction in island area despite the upward trend in sea level. Consequently, islands have predominantly been persistent or expanded in area on atoll rims for the past 20 to 60 yr.

Persistence of reef islands does not necessarily equate to geomorphic stability and the results also show that despite small net changes in island area most islands have experienced larger gross changes. The results show that reef islands are morphologically dynamic features that can change their position on reef platforms (e.g. lagoon migration) at a range of timescales. Characteristic planform adjustments in islands include: ocean shoreline erosion, lagoon progradation and, lateral extension of elongate islands. Mechanisms driving these observed changes are varied and can include a combination of sea-level rise, decadal-scale variations in wind and wave climate and anthropogenic impacts. Aggregated to the island scale these shoreline changes indicate that islands have adjusted their nodal position on reef surfaces. Over 65% of islands examined have migrated toward the lagoon (away from the reef edge) across the period of analysis.

Of significance, the results of this study on atoll islands are applicable to islands in other reef settings, as the boundary controls on island formation and change are comparable. Results of this study contradict widespread perceptions that all reef islands are eroding in response to recent sea level rise. Importantly, the results suggest that reef islands are geomorphically resilient landforms that thus far have predominantly remained static or grown in area over the last 20–60 yr. Given this positive trend, reef islands may not disappear from atoll rims and other coral reefs in the near-future as speculated. However, islands will undergo continued geomorphic change. Based on the evidence presented in this study it can be expected that the pace of geomorphic change may increase with future accelerated sea level rise. Results do not suggest that erosion will not occur. Indeed, as found in 15% of the islands in this study, erosion may occur on some islands. Rather, island erosion should be considered as one of a spectrum of geomorphic changes that have been highlighted in this study and which also include: lagoon shoreline progradation; island migration on reef platforms; island expansion and island extension. The specific mode and magnitude of geomorphic change is likely to vary between islands. Therefore, island nations must better understand the pace and diversity of island morphological changes and consider the implications of island persistence and morphodynamics for future adaptation.

7. Uncited references

Connell, 2003
Woodroffe, 2005

References

Anders, F.J., Byrnes, M.R., 1991. Accuracy of shoreline change rates as determined from maps and aerial photographs. Shore and Beach 59, 17–26.

Aston, J.P., 1995. The relative mobilities of coral cays on the GBR can be modelled, M.S. thesis, James Cook University., Townsville. 267 p.

Baines, G.B.K., McLean, R.F., 1976. Sequential studies of hurricane bank evolution at Funafuti atoll. Marine Geology 21, M1–M8.

Barnett, J., Adger, W.N., 2003. Climate dangers and atoll countries. Climatic Change 61, 321–337.

Bayliss-Smith, T.P., 1988. The role of hurricanes in the development of reef islands, Ontong Java Atoll, Solomon Islands. Geographical Journal 154, 377–391.

Brown, B.E., Dunne, R.P., 1988. The impact of coral mining on coral reefs in the Maldives. Environmental Conservation 15, 159–165.

Chivas, A., Chappell, J., Polach, H., Pillans, B., Flood, P., 1986. Radiocarbon evidence for the timing and rate of island development, beach–rock formation and phosphatization at Lady Elliot Island, Queensland, Australia. Marine Geology 69, 273–287.

Church, J.A., White, N.J., 2006. A twentieth century acceleration in global sea level rise. Geophysical Research Letters 33, L01602. doi:10.1029/2005GL024826.

Church, J.A., White, N.J., Coleman, R., Lambeck, K., Mitrovica, J.X., 2004. Estimates of the regional distribution of sea level rise over the 1950–2000 period. Journal of Climatology 17, 2609–2625.

Church, J.A., White, N.J., Hunter, J.R., 2006. Sea-level rise at tropical Pacific and Indian Ocean islands. Global and Planetary Change 53, 155–168.

Connell, J., 1999. Environmental change, economic development, and emigration in Tuvalu. Pacific Studies 22, 1–20.

Connell, J., 2003. Losing ground? Tuvalu, the greenhouse effect and the garbage can. Asia Pacific Viewpoint 44, 89–106.

Connell, J., 2004. Environmental change, economic development, and emigration in Tuvalu. In: Lockwood, Victoria S. (Ed.), Globalization and Culture Change in the Pacific Islands. Pearson, Prentice Hall, Upper Saddle River, New Jersey, pp. 260–272.

Cooper, J.A.G., Pilkey, O.H., 2004. Sea level rise and shoreline retreat, time to abandon the Bruun Rule. Global and Planetary Change 43, 157–168.

Cowell, P.J., Kench, P.S., 2001. The morphological response of atoll islands to sea-level rise. Part 1: modifications to the shoreline translation model. Journal of Coastal Research 34, 633–644 Special Issue.

Crowell, M., Leatherman, S.P., Buckley, M.K., 1991. Historical shoreline change: error analysis and mapping accuracy. Journal of Coastal Research 7, 839–852.

Dickinson, W.R., 1999. Holocene sea-level record on Funafuti and potential impact of global warming on central Pacific atolls. Quaternary Research 51, 124–132.

Flood, P.G., 1986. Sensitivity of coral cays to climatic variations, southern Great Barrier Reef, Australia. Coral Reefs 5, 13–18.

Flood, P.G., Jell, J.S., 1977. The effects of cyclone 'David' on the sediment distribution patterns on Heron Reef, Great Barrier Reef, Australia. Proceedings of the Third International Coral Reef Symposium, pp. 119–125.

Graham, R., Koh, A., 2003. Digital Aerial Survey: Theory and Practice. Whittles Publishing, Caithness, Scotland.

Harmelin-Vivien, M.L., 1994. The effects of storms and cyclones on coral reefs: a review. Journal of Coastal Research 12, 211–231 SI.

Hayne, M., Chappell, J., 2001. Cyclone frequency during the last 5000 years at Curacao Island, north Queensland, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 168, 207–219.

Kahn, T.M.A., Quadir, D.A., Murty, T.S., Kabir, A., Aktar, F., Sarker, M.A., 2002. Relative sea level changes in Maldives and vulnerability of land due to abnormal coastal inundation. Marine Geodesy 25, 133–143.

Kench, P.S., Brander, R.W., 2006. Response of reef island shorelines to seasonal climate oscillations: South Maalhosmadulu Atoll, Maldives. Journal of Geophysical Research 111, F01001. doi:10.1029/2005JF000323.

Kench, P.S., Cowell, P.J., 2001. The morphological response of atoll islands to sea-level rise. Part 2: application of the modified shoreface translation model (STM). Journal of Coastal Research 645–656 ICS 2000.

Kench, P.S., Harvey, N., 2003. Monitoring coastal change in Pacific atoll environments: the Pacific atoll coastal monitoring and analysis network (PACMAN). In: Kench, P.S., Hume, T.M. (Eds.), Proceedings of the Coasts and Ports Australasian Conference, 2003, Auckland, New Zealand. Paper 75. 10 pp.

Kench, P.S., McLean, R.F., Nichol, S.L., 2005. New model of reef-island evolution: Maldives, Indian Ocean. Geology 33, 145–148.

Kench, P.S., McLean, R.F., Brander, R.F., Nichol, S.L., Smithers, S.G., Ford, M.R., Parnell, K.E., Aslam, M., 2006. Geological effects of tsunami on mid-ocean atoll islands: the Maldives before and after the Sumatran tsunami. Geology 34, 177–180.

Kench, P.S., Smithers, S.G., McLean, R.F., Nichol, S.L., 2009a. Holocene reef growth in the Maldives: evidence of a mid-Holocene sea level highstand in the central Indian Ocean. Geology 37 (5), 455–458.

Kench, P.S., Perry, C.T., Spencer, T., 2009b. Coral Reefs. Chapter 7. In: Slaymaker, O., Spencer, T., Embleton-Hamann, C. (Eds.), Geomorphology and Global Environmental Change. Cambridge University Press, Cambridge, pp. 180–213.

Leatherman, S.P., 1997. Island States at Risk: Global Climate Change, Development and Population. Coastal Education Research Foundation, Florida. 242 p.

Maragos, J.E., 1993. Impact of coastal construction on coral reefs in the U.S.-affiliated Pacific Islands. Coastal Management 21, 235–269.

Maragos, J.E., Baines, G.B.K., Beveridge, P.J., 1973. Tropical cyclone creates a new land formation on Funafuti atoll. Science 181, 1161–1164.

McLean, R.F., Hosking, P.L., 1991. Geomorphology of reef islands and atoll motu in Tuvalu. South Pacific Journal of Natural Science 11, 167–189.

Milne, G.A., Gehrels, W.R., Hughes, C.W., Tamisiea, M.E., 2009. Identifying the causes of sea-level change. Nature Geoscience 2, 471–478. doi:10.1038/NGEO544.

Mimura, N., 1999. Vulnerability of island countries in the South Pacific to sea level rise and climate change. Climate Research 12, 137–143.

Mimura, N., Nurse, L., McLean, R.F., Agard, J., Briguglio, L., Lefale, P., Sem, G., 2007. Small islands. Climate change 2007: impacts, adaptation and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikoff, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 687–716.

Moore, L.J., 2000. Shoreline mapping techniques. Journal of Coastal Research 15, 111–124.

Roy, P., Connell, J., 1991. Climatic change and the future of atoll states. Journal of Coastal Research 7, 1057–1096.

Sheppard, C., Dixon, D., Gourlay, M.R., Sheppard, A., Payet, R., 2005. Coral mortality increases wave energy reaching shores protected by reef flats: examples from Seychelles. Estuarine, Coastal and Shelf Science 64, 223–234.

Solomon, S.M., Forbes, D.L., 1999. Coastal hazards, and associated management issues on South Pacific Islands. Ocean and Shoreline Management 42, 523–554.

Stoddart, D.R., 1963. Effects of Hurricane Hattie on the British Honduras reefs and cays, October 30–31, 1961. Atoll Research Bulletin 95, 1–142.

Stoddart, D.R., 1971. Environment and history in Indian Ocean in reef morphology. In: Stoddart, D.R., Yonge, C.M. (Eds.), Symposium of the Zoological Society of London, Vol. 28, pp. 3–38.

Stoddart, D.R., Steers, J.A., 1977. The nature and origin of coral reef islands. In: Jones, O.A., Endean, R. (Eds.), Geology 2. : Biology and Geology of Coral Reefs, Vol. IV. Academic Press, pp. 59–105.

Stoddart, D.R., McLean, R.F., Scoffin, T.P., Gibbs, P.E., 1978. Forty five years change on low wooded islands, Great Barrier Reef. Philosophical Transactions of the Royal Society of London 284, 63–80.

Stoddart, D.R., Fosberg, F.R., Spellman, D.L., 1982. Cays of the Belize barrier reef and lagoon. Atoll Research Bulletin 256, 1–76.

Taylor, J., 1924. Movement of sand cays. Queensland Geographical Journal 39, 38–39.

Thieler, E.R., Danforth, W.W., 1994. Historical shoreline mapping (I): improving techniques and reducing positioning errors. Journal of Coastal Research 10, 549–563.

Umbgrove, J.H.F., 1947. Coral reefs of the East Indies. Geological Society of America Bulletin 58, 729–777.

Verstappen, H.Th., 1954. The influence of climatic change on the formation of coral islands. American Journal of Science 252, 428–435.

Webb, A.P., 2006. Coastal change analysis using multi-temporal image comparisons — Funafuti Atoll. SOPAC Technical Report 54.

Woodroffe, C.D., 2005. Late Quaternary sea-level highstands in the central and eastern Indian Ocean: a review. Global and Planetary Change 49, 121–138.

Woodroffe, C.D., 2008. Reef–island topography and the vulnerability of atolls to sea-level rise. Global and Planetary Change 62, 77–96.

Woodroffe, C.D., McLean, R.F., 1992. Kiribati vulnerability to accelerated sea-level rise: a preliminary study. ADFA Report to Department of Arts, Sports, Environment and territories, Government of Australia, Canberra, ACT, Australia. 82 p.

Woodroffe, C.D., McLean, R.F., 1993. Cocos (Keeling) Islands vulnerability to sea-level rise. Report to the Climate Change and Environmental Liaison Branch, Depart of Arts, Sports, Environment and territories, Government of Australia, Canberra, ACT, Australia. 82 p.

Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A., Gehrels, W.R., 2009. Evidence for the acceleration of sea level on multi-decade and century timescales. International Journal of Climatology 29, 777–789.

Yamano, H., Kayanne, H., Yamaguchi, T., Kuwhara, Y., Yokoki, H., Shimazaki, H., Chikamori, M., 2007. Atoll island vulnerability to flooding and inundation revealed by historical reconstructions: Fongafale Islet, Funafuti Atoll, Tuvalu. Global and Planetary Change 57, 407–416.

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