Historical area and shoreline change of reef islands around Tarawa Atoll, Kiribati

Naomi Biribo & Colin D. Woodroffe

Sustainability Science

ISSN 1862-4065
Volume 8
Number 3

Sustain Sci (2013) 8:345-362
DOI 10.1007/s11625-013-0210-z

Springer

Sustain Sci (2013) 8:345–362
DOI 10.1007/s11625-013-0210-z

SPECIAL FEATURE: ORIGINAL ARTICLE

Understanding and Managing Global Change in Small Islands

Historical area and shoreline change of reef islands around Tarawa Atoll, Kiribati

Naomi Biribo · Colin D. Woodroffe

Received: 1 September 2012 / Accepted: 7 April 2013 / Published online: 9 May 2013

Abstract Low-lying reef islands on atolls appear to be threatened by impacts of observed and anticipated sea-level rise. This study examines changes in shoreline position on the majority of reef islands on Tarawa Atoll, the capital of Kiribati. It investigates short-term reef-island area and shoreline change over 30 years determined by comparing 1968 and 1998 aerial photography using geographical information systems. Reef islands have substantially increased in size, gaining about 450 ha, driven largely by reclamations on urban South Tarawa, accounting for 360 ha (~80 % of the net change). Widespread erosion and high average accretion rates appear to be related to disjointed reclamations. In rural North Tarawa, most reef islands show stability, with localised changes in areas such as embayments, sand spits and beaches adjacent to, or facing, inter-island channels. Shoreline changes in North Tarawa are largely influenced by natural factors, whereas those in South Tarawa are predominantly affected by human factors and seasonal variability associated with El Niño—Southern Oscillation (ENSO). However, serious concerns are raised for the future of South Tarawa reef islands, as evidence shows that widespread erosion along the ocean and lagoon shorelines is primarily due to human activities and further encroachment onto the active beach will disrupt longshore sediment transport, increasing erosion and susceptibility of the reef islands to anticipated sea-level rise. Appropriate adaptation measures, such as incorporating coastal processes and seasonal variability associated with ENSO when designing coastal structures and developing appropriate management plans, are required, including prohibiting beach mining practices near settlements.

Keywords Atoll · Sea-level rise · Shoreline change · Tarawa Atoll · Kiribati

Handled by John E. Hay, Ibaraki University, Japan.

Portions of this paper were originally presented at the LOICZ Open Science Conference, Session A4, Yantai, China, September 2011.

N. Biribo · C. D. Woodroffe (✉)
School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia
e-mail: colin@uow.edu.au

N. Biribo
e-mail: nb766@uowmail.edu.au

Introduction

Low-lying reef islands on the perimeter of coral atolls are threatened by the impacts of climate change, particularly observed and anticipated sea-level rise (Nicholls et al. 2007). Such reef islands are composed of biogenic sediments derived from the skeletal remains and breakdown of calcareous organisms, such as coral, coralline algae and foraminifera, that live on the adjacent reefs. Sea-level rise appears likely to have at least three types of impact on reef islands: inundation of low-lying areas, erosion of shorelines and saline intrusion into the freshwater lens (Mimura 1999; Woodroffe 2008; Terry and Chui 2012). However, there is currently no scientific consensus on the responses of reef islands to rising sea level. The number of studies carried out across an entire atoll to determine shoreline responses to recent gradual sea-level rise, or area changes across all reef islands on an atoll, is also limited.

Increased inundation of the lowest parts of reef islands appears inevitable as extreme water levels get higher. Widespread flooding in the interior of Fongafale on Funafuti Atoll, in Tuvalu, is often cited as confirmation that "islands are sinking" (Patel 2006). However, Yamano et al. (2007) reconstructed historical conditions showing that the interior of this reef island was already subject to flooding at the time of the Royal Society expedition in the 1890s, that airfield construction further increased areas subject to inundation and that the considerable degree of human modification, including urbanisation, has exacerbated the problem in this case.

There is similarly a widespread perception that reef island shorelines directly exposed to increased wave action are likely to erode, resulting in a reduction in reef island size and their eventual disappearance. Erosion along shorelines behind degraded reefs following coral bleaching in the Seychelles has been invoked as an analogue for the likely response to future sea-level rise (Sheppard et al. 2005). In contrast, an alternative view is that, as a result of more prolific coral growth and enhanced sediment transport on reef flats when the sea is higher, shorelines will actually experience accretion, thus, increasing reef island size (Kinsey and Hopley 1991). A recent analysis of changes in area of 27 reef islands from several Pacific atolls for periods of 35 or 61 years concluded that they were growing (Webb and Kench 2010). The results of that study indicated that 86 % of the examined reef islands showed growth or stability. Only 14 % of those studied reduced in size. Four reef islands on Tarawa Atoll, the capital of the Republic of Kiribati, contributed disproportionately to this conclusion. In descending order, based on their proportional increase, these were Betio (increased by 30 %), Bairiki (16.3 %), Nanikai (12.5 %) and Buariki (2.9 %) (Table 1). The first three are located in urban South Tarawa and represent the most rapidly accreting reef islands in the study. Their study also concluded that ocean-facing shorelines located on the windward side of reef islands displayed erosion, but that lagoon beaches facing away from ocean swell, primarily responded by net accretion. However, it is not clear how widespread these responses are, or that the reef islands selected on Tarawa are representative of other reef islands on that atoll or of other atolls in the region.

The shorelines of reef islands are dynamic features which are largely dependent on the balance between sediment availability and oceanographic processes (Kench and Cowell 2002). A range of physical factors lead to shoreline change on reef islands, including the size and morphology of reef islands, their location on the reef rim and their relative exposure to prevailing winds, storms and seasonal variability of the sea level (McLean 2011). Also important is the availability of sediments to build and maintain reef islands, either derived from productive oceanward reefs or sources in the sediment-rich lagoon (Woodroffe and Morrison 2001). Human factors, such as reclamations, groynes or seawalls that alter or interrupt coastal processes around reef islands also influence shoreline changes on atolls. Ford (2012) determined that human activities are largely responsible for the changes observed over 34–37 years on Majuro Atoll in the Marshall Islands to the north of Kiribati. Major developments on both the ocean and lagoon shorelines, such as reclamations, have modified the land, with the largest increase having a proportion of 67.5 % of the entire island size, being associated with the construction of the international airport. Erosion of lagoon beaches in rural areas appears to be related to coastal structures in urban areas interrupting the longshore sediment transport (Ford 2012).

Other studies of Pacific atolls indicate a greater complexity in shoreline response. Long-term shoreline changes over a period of 40 years (1969–2009) on Maiana Atoll, an atoll just south of Tarawa in the Gilbert Group and which has undergone little anthropogenic impact, suggest that the growth of reef islands is largely natural, with slow accretion rates (Rankey 2011). Both long- and short-term shoreline changes on large reef islands located on the windward side of Maiana, and another atoll in the Gilbert chain called Aranuka, indicate local changes occurring on the ends of reef islands that are associated with changing wind conditions. However, increased erosion on the eastern shorelines of Maiana and Aranuka reef islands located on the windward side appeared to be related to exposure to wind and wave energy during the strong La Niña period of 2005–2009 (Rankey 2011), indicating that oceanographic conditions associated with El Niño—Southern Oscillation (ENSO) can play an important role in explaining reef island behaviour in Kiribati.

This paper examines the morphological change of reef islands around the entire rim of Tarawa Atoll. The atoll has been selected as it serves as the capital of Kiribati, with South Tarawa as the centre of government, development,

Table 1 Summary of changes to Tarawa reef islands of over a period of 35 or 61 years (1943–2004)

Reef islands	Time period (years)	Initial area (ha)	Final area (ha)	Net change (ha)	Rate of change (ha/year)	% change
Betio	61 (1943–2004)	120.03	156.00	36.00	0.5	+30.0
Nanikai	35 (1969–2004)	6.40	7.20	0.80	0.02	+12.5
Bairiki	35 (1969–2004)	35.46	41.25	5.79	0.2	+16.3
Buariki	61 (1943–2004)	338.30	348.40	10.10	0.2	+2.9

Modified from Webb and Kench (2010)

economics and population. Any future shoreline changes to the reef islands of this atoll would be very important, as they serve as home to a population of more than 56,000 (Ministry of Finance and Economic Planning 2010). This study summarises well-documented changes that have been recorded by successive studies undertaken by the Applied Geoscience and Technology Division of the Secretariat of the Pacific Community (SOPAC) focused on the shoreline around the densely populated central business districts on Betio and Bairiki, indicating the effects of both ENSO and human activities. It then examines shorelines for the entire atoll over different periods of time by comparing shoreline positions from aerial photography taken 30 and 64 years apart. This involves investigating the historical shoreline and area changes, including their trends, over the past several decades to provide background context for changes that are likely to occur in the future.

Area of study

Tarawa Atoll (1°30′N, 173°00′E) is the capital of the Republic of Kiribati and is part of the Gilbert Group. It is a triangular atoll with a north–south length of 40 km and a maximum width of 25 km. The lagoon, with a maximum depth of only 24 m, is partially enclosed by a chain of elongate and small complex reef islands on the northeastern and southern perimeters, but the submerged reef rim to the west allows unrestricted circulation between lagoon and ocean waters (Fig. 1). The atoll is administratively divided into two parts: North Tarawa (rural) and South Tarawa (urban). The reef islands of North Tarawa are rarely more than 100–400 m wide and lie on outcrops of conglomerate ranging from <0.5 to 1.0 m in height above the reef flat (Richmond 1993). These conglomerates often outcrop, extending across the reef flats as prominent shore-normal groyne-like features (Richmond 1993). They can be exposed in the centre of reef islands, and also extend into the subsurface, as observed in some cores (Marshall and Jacobson 1985).

Radiocarbon dating of reef-island sediments indicates that they have accumulated over the past 4,500 years, with gradual oceanward accretion constructing a beach ridge that is typically 2–3 m above sea level along the ocean shore, as shown for other reef islands in the Gilbert chain (Richmond 1992; Woodroffe and Morrison 2001). Radiocarbon ages of single *Amphistegina* foraminifera sampled from pits dug along a transect on the reef island of Tabiteuea indicate an oceanward depositional pattern, with the oldest aged foraminiferal fossils of around 4,500 years BP obtained about three quarters of the width of the reef island from the ocean side, and ages becoming progressively younger towards the ocean, consistent with an oceanward accretion pattern. On the lagoon side, there was a slower accretion, as would be expected under the oceanward accretion mode interpreted for the island of Makin, the northernmost of the Gilbert chain of atolls in Kiribati, by Woodroffe and Morrison (2001). The reef islands of North Tarawa lie behind a reef flat that is several hundred metres wide and is directly exposed to the easterly trade winds, whilst those on South Tarawa lie parallel to the dominant winds.

The climate of the Gilbert chain of atolls, spanning the equator, is governed by several features, namely, the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ) and trade winds. Wind direction and strength is related to the Southern Oscillation Index (SOI). A positive SOI is associated with La Niña, a negative SOI is associated with El Niño, during which the easterly trade winds weaken, and there are stronger westerly winds. Tarawa lies outside the region of the Pacific that experiences tropical cyclones; however, strong west to northwest winds generated from cyclones do occur. Wind variability and duration depend on ENSO conditions and, thus, ENSO has an influence on the sea level. Although the atoll experiences a tidal range of more than 2 m, the mean monthly sea level is strongly linked to ENSO and can vary by more than 0.4 m; for example, there was a drop of this magnitude following the 1997–98 El Niño (Donner 2012). Current sea-level analysis based on data recorded from two tide gauges installed in Betio, Tarawa, shows an average linear rise of 1.8 mm/year over the 35 years since 1974 (Ramsay et al. 2010).

Although there are passages between many of the reef islands on North Tarawa, some have been obstructed by causeways. The chain of reef islands in South Tarawa has been artificially connected by causeways of solid fill that limit lagoonal flushing, except in two cases. Betio, the westernmost reef island, and Bairiki are the most densely populated reef islands, and represent the commercial and government centres, respectively.

There have been several shoreline studies that have focussed on the densely populated reef islands on South Tarawa, particularly Betio (but also considering Bairiki and Bonriki–Taborio), due to concerns related to population pressures and erosion following causeway construction. It is clear that human activities have shaped Betio. During World War II, the reef island was heavily fortified by the Japanese with bunkers and gun emplacements. After the war, the Americans cleaned up Betio, by collecting war debris and dumping it on the west coast (Gillie 1993). Time series of shoreline positions over the past 49 years from 1943 to 1992 show that Betio has accreted by 23 ha, which is a 20 % increase of the total reef island area (Gillie 1993), although with some sections that have eroded (Fig. 2). The particularly high rate of 'growth' determined for this reef

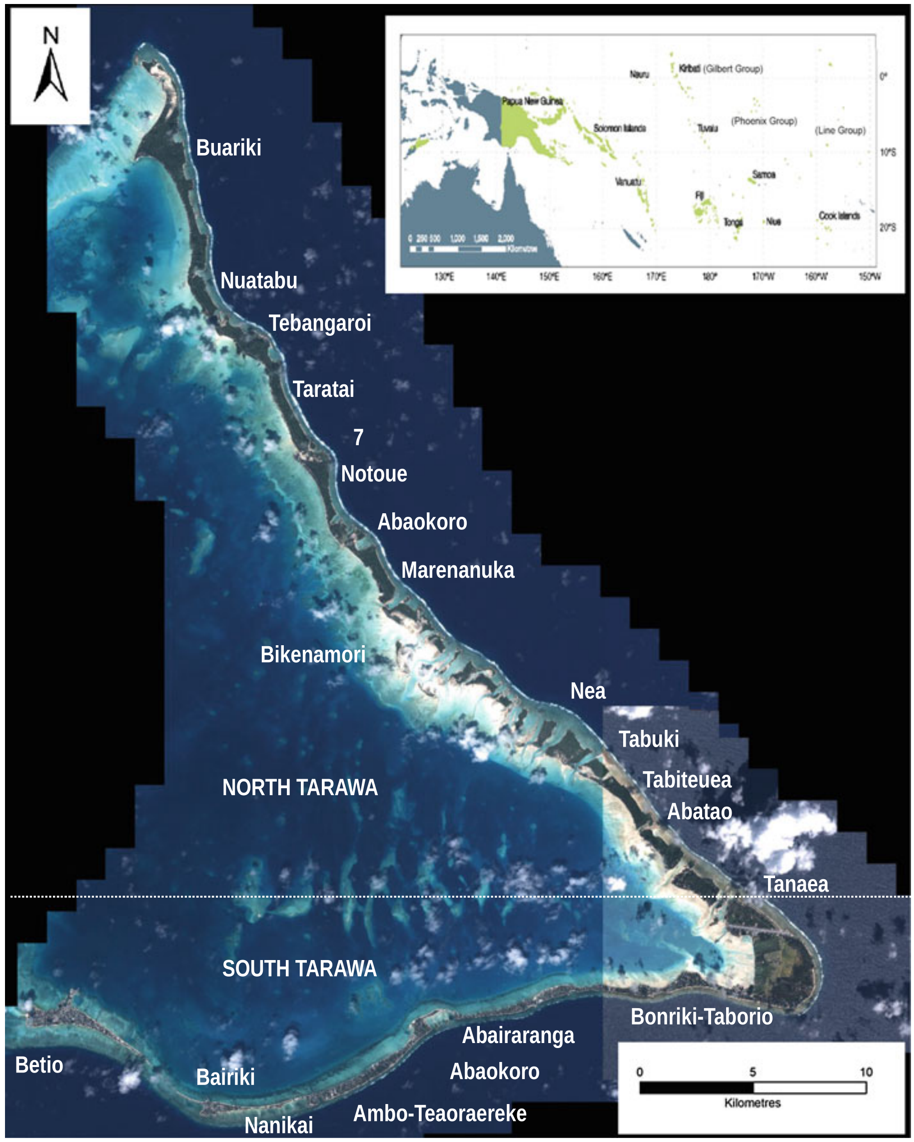

Fig. 1 IKONOS satellite image of Tarawa Atoll in 2003 showing the study area (image copyright GeoEye). The *inset* shows the location of Kiribati in relation to the other Pacific countries (source: Australian Bureau of Meteorology and CSIRO 2011, p 8)

island by Webb and Kench (2010) is primarily an outcome of such interventions.

Several SOPAC studies have shown that the shorelines of South Tarawa are also very sensitive to wind and wave fluctuations associated with ENSO (Burne 1983; Byrne 1991). For example, numerous beach profiles have been surveyed since 1982 (Fig. 2). Analysis of 7 years of beach profiling data demonstrated that lagoon shorelines were more dynamic than ocean shorelines, and implied that ENSO plays a significant role in terms of sediment dynamics (Harper 1989). Sediment transport along South Tarawa during normal conditions is predominantly westward, resulting from prevailing easterly winds, but El Niño reverses the direction of the predominant longshore sediment transport to the east (Byrne 1991; Harper 1989).

On the basis of the observations that shoreline changes around reef islands are influenced by ENSO variability, it was inferred by Solomon (1997) that the expansion of the surface area of Betio was likely to be atypical of other reef islands, both elsewhere on Tarawa and, perhaps, also in other parts of the Pacific.

Materials and methods

Historic shoreline changes can be measured by comparing shoreline positions over decades as detected from aerial photography or imagery, using tools such as Digital Shoreline Analysis System (DSAS) software developed by the United States Geological Survey (USGS), which has been used to standardise shoreline change analysis (Morton et al. 2004). To compare shoreline changes, an appropriate shoreline proxy should be selected that can be identified on each aerial photograph or image. Shoreline indicators need

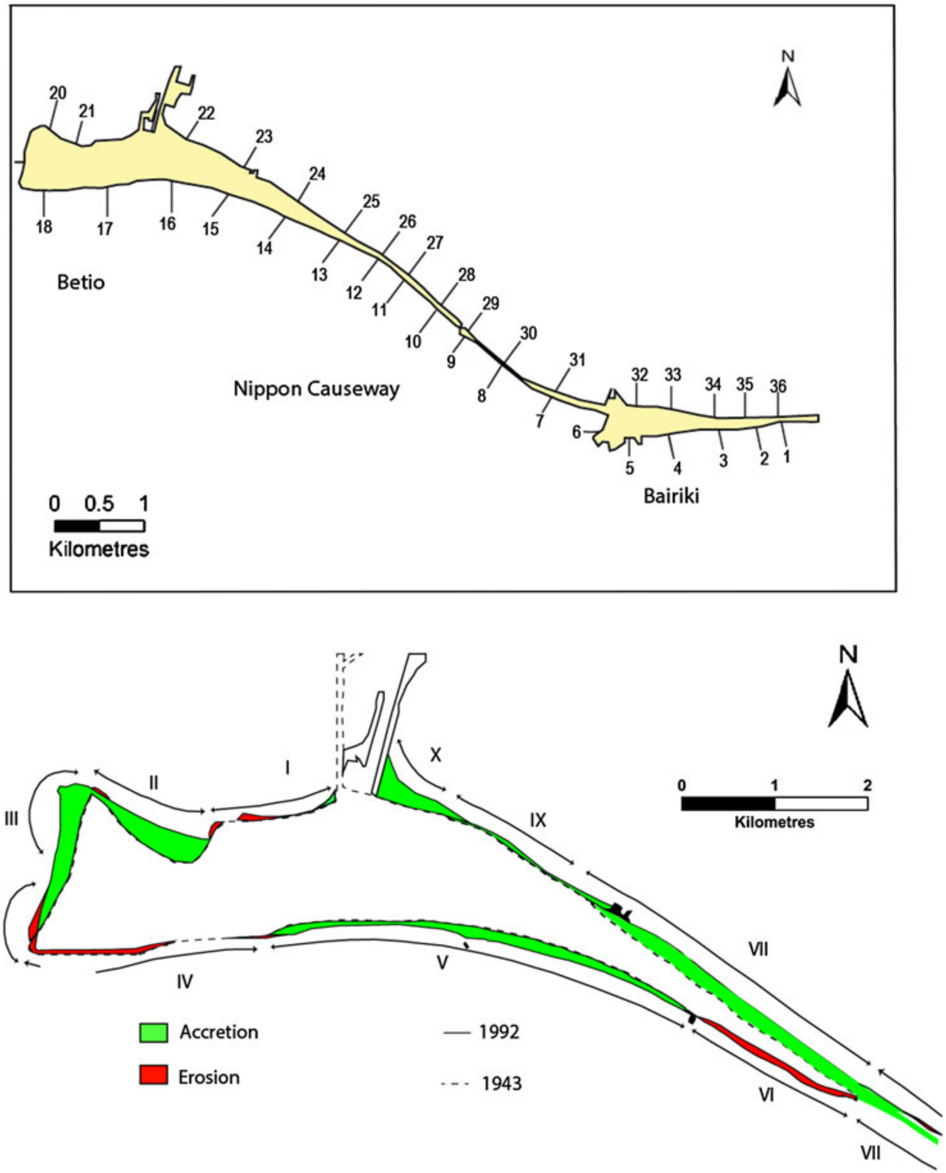

Fig. 2 Map of the reef islands of Betio and the government centre of Bairiki, linked by the Dai Nippon Causeway. The *upper figure* shows the location of beach profiling sites established in the 1980s by SOPAC. The *lower figure* indicates the sections of the shoreline of Betio mapped by Gillie (1993) and the trends in accretion and erosion between 1943 and 1992

to be detectable at different time periods to allow repetition (Boak and Turner 2005). Examples of commonly used shoreline indicators are high water line, base of the beach, debris line, landward edge of coastal protection structures, mean high water line and vegetation line. On atolls, the vegetation line (VL) is generally distinct, particularly where it is composed of a dense scrub of *Scaevola* on the oceanside beach-ridge crest, providing a good indication of the top of the beach. On the other hand, the abrupt change in slope and substrate where the unconsolidated beach sand meets the solid reef flat means that the base of the beach (BB) is a particularly prominent line that can be easily detected along most of the ocean shores (Fig. 3). The base of the beach was also used as a shoreline indicator by Rankey (2011) in his study on Aranuka and Maiana Atolls.

The following procedure was carried out to prepare the aerial photographs for shoreline analysis using DSAS 4.2. Aerial photos were acquired as tiff files scanned at a high resolution of 1,200 dpi. The base map (comprising digital files derived from the 1998 aerial photographs), originally in Tarawa Local Grid, was transformed to Universal Transverse Mercator (UTM) Zone N59. Georeferencing was carried out at a scale of 1:1,000. Digital images were georeferenced by selecting at least 6 up to a maximum of 30 ground control points (GCP) on each photo, well spaced to reduce distortion and error. Features such as fish traps or outcrops of conglomerate were used to georeference 1943 and 1968 aerial photographs. A 2007 Quickbird satellite image also required georeferencing, as there was an average shift of about four metres (false easting) between these data and the re-projected 1998 photographs (Table 2). Georectification used the spline

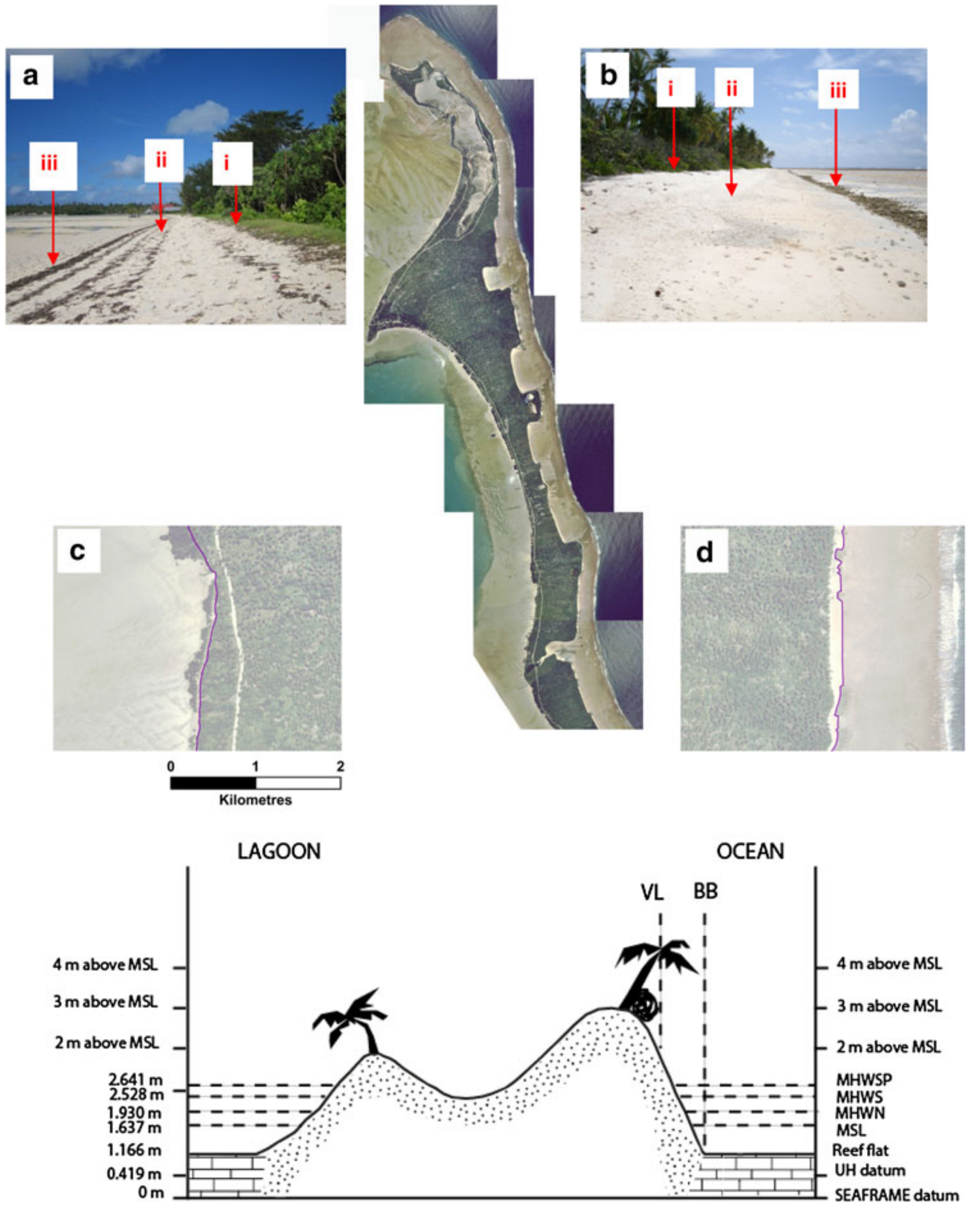

Fig. 3 Shoreline indicators used in this study, as illustrated by the reef island Buariki, the northernmost reef island on Tarawa Atoll. Potential shoreline indicators include the vegetation line (VL), which, on the oceanward beach, is often the outer edge of *Scaevola* scrub (marked by *i* in parts **a**, **b**); former high-water lines (HWL) on the beach (marked by *ii* in parts **a**, **b**); and the base of the beach (BB, marked by *iii* in parts **a**, **b**), which is prominent where the sandy beach meets the reef flat. This 'base of beach' is marked by the *digitised line* on the aerial photograph. The *lower panel* shows a schematic cross-section of a reef island, illustrating the relationship between different water levels, shoreline indicators applied in this study and the University of Hawaii (UH) and SEAFRAME tide gauges

Table 2 Attributes of aerial photography and imagery utilised in this study

Image	Date of acquisition	Scale/resolution	Colour	Source
Aerial photos	25/01/1943	1:10,000	Black and white	Kiribati Lands Division
Aerial photos	14/07/1968 and 14/06/1969	1:10,000	Black and white	Kiribati Lands Division
Aerial photos	13–19/06/1998	1:2,500	Colour	Schlencker Mapping Pty Ltd., Australia
Quickbird satellite imagery	03/07/2007	±0.6 m	Colour	GeoEye, USA

method to reduce distortion. Quality control was performed to ensure that the images were accurate within ±0.5 m (1:2,500 base map scale) by checking the registration of persistent features, such as conglomerate outcrops.

An aerial photograph of the northernmost reef island, Buariki, acquired by Schlencker Mapping in 1998 as part of photogrammetric mapping of the entire atoll (e.g. Fig. 3, centre) shows examples of ocean and lagoon shores; the eastern shoreline comprises a wide ocean-facing reef flat. The vegetation line on the oceanward beach is marked by (i) in Fig. 3b. Former high-water lines on the beach (marked by ii in Fig. 3b) may be discernible. The base of

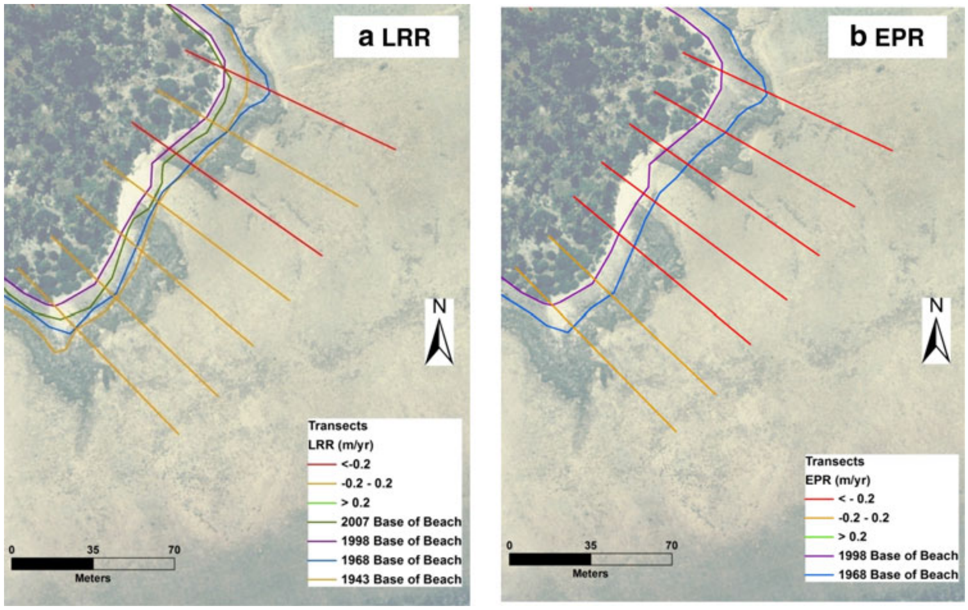

Fig. 4 Part of a 1998 aerial photograph of a representative reef island (Abairaranga), showing the position for the base of the beach for 1968 and 1998. On these figures, the LRR (**a**) method has been used to determine shoreline trend over the 64 years from 1943 to 2007, and the same reef island with less shorelines over this 30-year period from 1968 to 1998, from which the shoreline trend has been determined by the LRR method. The LRR results show that the coastline is predominantly stable (more *orange* transects), whilst EPR shows predominant erosion (*red* transects). However, visual analysis of the shorelines in **a** suggests more shoreline fluctuations than are indicated by the results

the beach (BB) marked by iii in Fig. 3b is shown by the digitised line on the aerial photograph; in places, BB occurs on conglomerate, where this crops out on the beach. On the western lagoon shore, similar shoreline indicators are shown; the vegetation line (i), former high-water line (ii) and base of the beach (iii). The base of the beach is not as distinct on lagoon shores because the sandy reef island sediments grade more gradually into the muddy sand of the lagoon flat. The vegetation line is shown by the digitised line on the aerial photograph (Fig. 3c); it is placed landward of mangroves (the extensive dark vegetation to the west of the line at the southern end of the aerial photograph) because these are inter-tidal and grow on the muddy lagoon flat and not on the reef island itself. A schematic cross-section of the reef island (Fig. 3) shows a morphology which comprises a high oceanward ridge, a topographically lower lagoon ridge and a central depression that is commonly excavated for the cultivation of *babai*. Also shown is the relationship between different water levels and the BB and VL shoreline indicators, and the gauge datums for both the University of Hawaii (UH) and SEAFRAME tide gauges.

The DSAS tool, an extension in ArcGIS, provides several ways to compare shoreline positions digitised from a series of aerial photographs or satellite images at different dates. A baseline for the shorelines is defined, from which orthogonal transects are generated along the shore at user-defined intervals. The tool offers a range of methods such as linear regression rate (LRR) and endpoint rates (EPR) to calculate the shoreline changes. LRR is the slope of a best fitting line (regression) drawn for those shorelines that intersect the orthogonal transects. It is used for estimating the long-term shoreline trend, but masks short-term beach behaviour (Thieler et al. 2009). LRR was used in this study to measure the change between the period 1943 and 2007 utilising the four time series of 1943, 1968, 1998 and 2007. EPR is the rate of change calculated by dividing the maximum shoreline displacement by the total time period (youngest to oldest date), and it was used to calculate the change within the 30-year period of 1968–1998, which can be done for about 90 % of the atoll (in contrast to the 1943 photography which was not available, or suitable, for as much of the atoll). For discussion purposes, the BB indicator will be used as its advantage over VL in that it captures the footprint of the reef islands, enabling an estimation of the island area. Figure 4 shows the application of the EPR method comparing the 1968 and 1998 BB shorelines, and the LRR method with respect to the 1943, 1968, 1998 and 2007 BB shorelines; the baseline and sample DSAS transects are illustrated. Some transects have been manually eliminated where they overlapped with other transects, as occurred at corners of embayments and coastal structures, or when transects have been constructed around coastal re-entrants that are partially enclosed within the land.

Transect measurements can show positive (accretion), negative (erosion) or no change (stability) of shorelines.

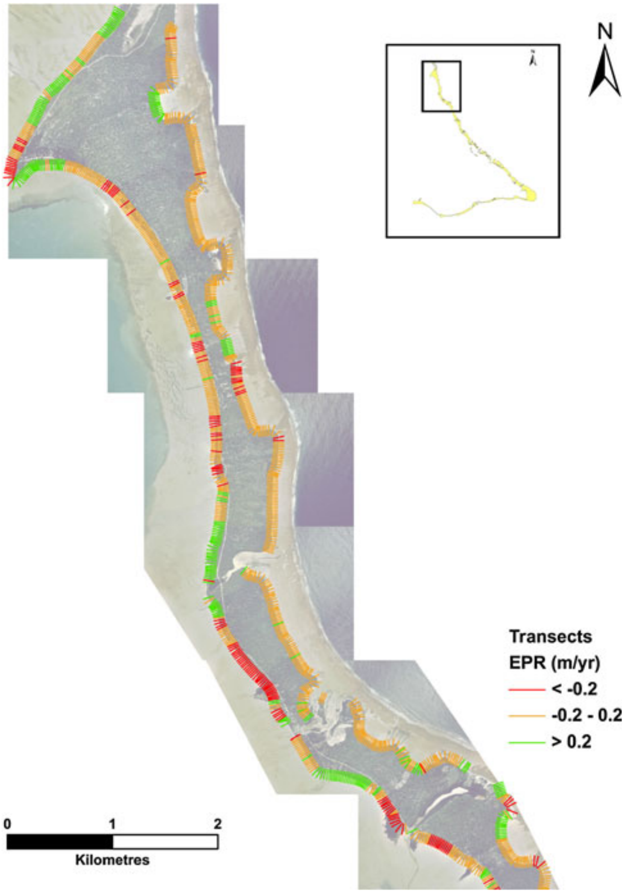

Fig. 5 Summary graphic illustrating the direction and rate of 30 years of shoreline change (1968–1998) on Buariki and adjacent reef islands (Nuatabu, Tebangaroi and northern part of Taratai), North Tarawa, overlain on the 1998 Schlencker aerial photograph. DSAS transects show the rate of change based on the EPR method using the base of the beach (BB), indicating erosion (*red*), stability (*amber*) and accretion (*green*)

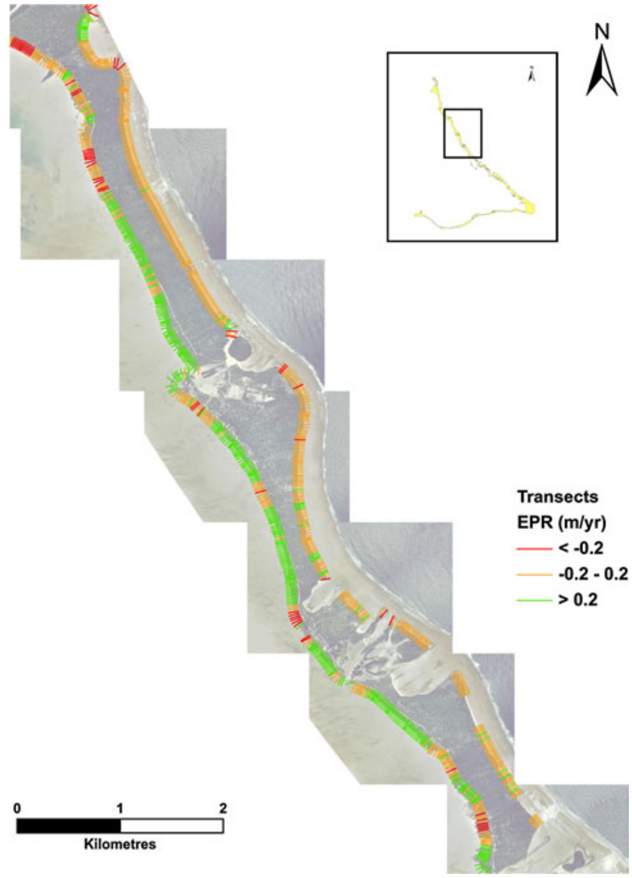

Fig. 6 Summary graphic illustrating the direction and rate of 30 years of shoreline change for North Tarawa (Taratai, Notoue, Abaokoro and Marenanuka reef islands), as for Fig. 5

Shoreline positions could be measured to within 3 m from 1998 and 1968 aerial photographs, such that a rate of change of the order of 0.1 m/year could be discriminated. Shoreline changes >0.1 m/year were considered to indicate measurable changes, as those of lower magnitude were below the resolution of the data. Based on limits of measurement and the scale of the aerial photograph of 1998, measured shoreline changes of between +0.2 and −0.2 m/year are considered to indicate stability (at the level of detection). Transects that record changes ≥+0.2 m/year indicate accretion and those ≥−0.2 m/year indicate erosion, and almost 6,000 transects are coloured accordingly (Figs. 5, 6, 7, 8 and 9).

Results

Digitisation of the reef island footprint enables estimation of changes of area over the 30-year period from 1968 to 1998. The results (Table 3) show that the total land area in 1968 was 2,370.68 ha. In 1998, the area had increased to 2,819.38 ha, a net increase of 448.70 ha, or 19 %. However, the increase is dominated by major developments, all in urban South Tarawa, which have built land from materials that have been sourced from the adjacent beach or surrounding nearshore areas. The developments (Table 4) have contributed 363.50 ha, and are, in turn, dominated by reclamation of Temaiku Bight, where 335 ha were empoldered to form additional land on Bonriki–Taborio, following the construction of a causeway and fishponds in 1970. Such developments are referred to as reclamations in Kiribati, involving the conversion of previously marine areas into land, not 're-claiming' areas that once were land that have been temporarily lost through inundation. Deducting this amount from the net increase of 448.70 ha, the land increase due to the combined effect of natural processes and 'small' developments (e.g. the numerous individual- or family-scale interventions that contribute to the increase, as discussed in more detail below for Bairiki) is estimated to be only 85.20 ha (or 19 % of the total). This analysis shows clearly that human activities contributed the

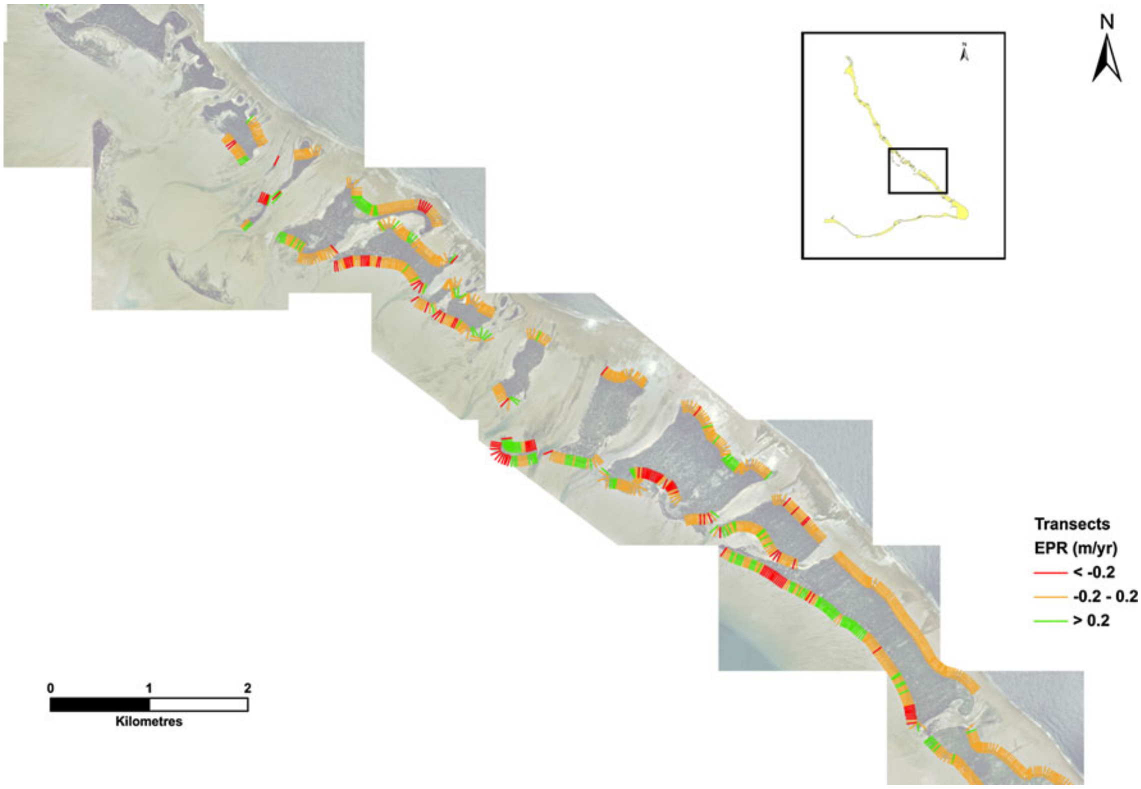

Fig. 7 Summary graphic illustrating the direction and rate of 30 years of shoreline change for central North Tarawa (for the reef islands north of and including Tabiteuea), as for Fig. 5

vast majority of the net increase of reef island area in Tarawa. Most changes were located on urban South Tarawa reef islands, including the reef islands that Webb and Kench (2010) used to derive their reported rates of reef island growth in relation to sea-level rise.

The area changes from 1968 to 1998 on the 40 reef islands located on North Tarawa, where population is absent or sparse, varied from reef island to reef island, as shown in Tables 5 and 6. Reef islands are generally stable, as there is minimal human impact on them. Twenty-five of the reef islands in this area showed no change at the level of detection, 13 showed net accretion and only two displayed net erosion. Net accretion amounted to 7.91 ha on Marenanuka, 6.63 ha on Notoue and 6.36 ha on Buariki, whereas on 7 reef islands, it was $\leq$1.5 ha. On elongate reef islands, accretion occurs on the southern tips, in areas facing inter-island channels and in ocean-facing embayments, as on northern Buariki. Accretion is also evident on sand spits and in areas where the channels have been blocked by causeways, allowing sediment to deposit on beaches adjacent to the causeways.

The results of DSAS transects show a range of change in BB shorelines from accretion at rates of up to +0.5 m/year to erosion at rates of up to −0.2 m/year (Tables 7, 8 and 9). Shoreline change data from the BB and VL indicators were summarised according to beach (ocean or lagoon) and location (North or South Tarawa). Figures 5, 6, 7 and 8 show accretion, erosion or stability on DSAS transects along sections of coast on 26 reef islands in North Tarawa. Ocean-facing beaches appear largely stable over this 30-year time period, with marked accretion on only two reef islands. Slightly more incidences of accretion are indicated on lagoon shores compared to that on the ocean beaches, although it is important to recognise that it is not as easy to unambiguously define the BB intersection between beach and lagoon flat on these shores. Greater variability is apparent along the lagoon shores than the ocean shores.

DSAS transects for reef islands subject to much greater human pressures (Figs. 8 and 9) illustrate greater change. The reef island of Bonriki–Taborio on which the airstrip is built has been extensively modified through reclamation of former lagoon flats in Temaiku Bight by the construction of the causeway for a series of projects producing fishponds and a connecting road. This area at the eastern end of the lagoon has not been included in the analysis because of these interventions. Abatao and Buota, to the north, are also subject to increasing human pressures as settlement spreads onto them. Extensive sections of both ocean-facing and lagoonal shores have undergone erosion along South Tarawa.

The style and extent of reef island area changes over the past 30 years (1968–1998) on the eight reef islands of

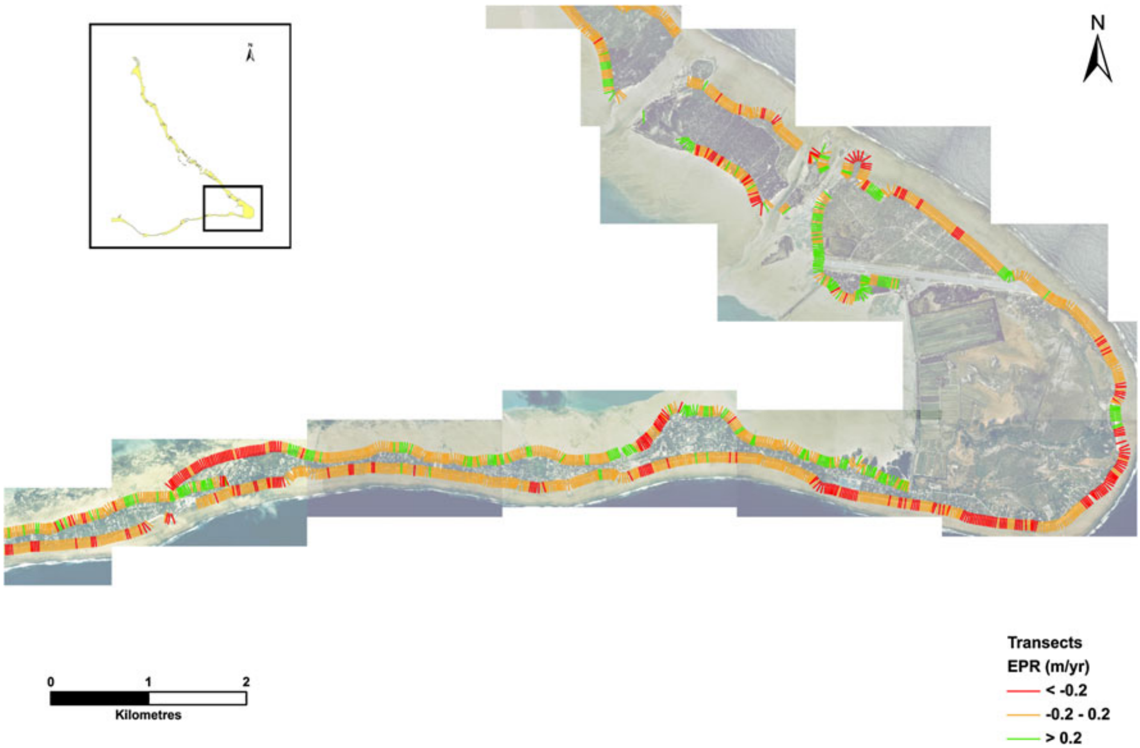

Fig. 8 Summary graphic illustrating the direction and rate of 30 years of shoreline change for South Tarawa (Abatao, Buota and part of Bonriki–Taborio, *upper* and western portion of Bonriki–Taborio, Ambo–Teaoraereke and Nanikai, *lower*), as for Fig. 5. Note the major modification of Temaiku Bight, the easternmost part of the lagoon, following the construction of a causeway in 1970, evident from the numerous fishponds

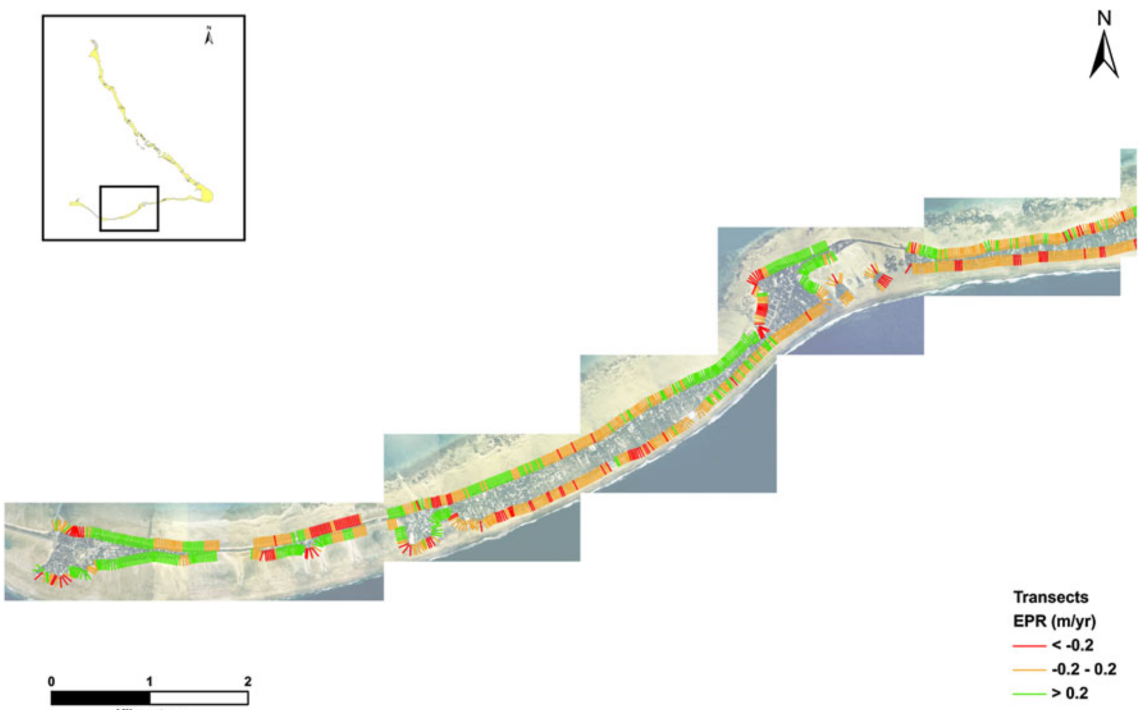

Fig. 9 Summary graphic illustrating the direction and rate of 30 years of shoreline change for South Tarawa (extreme western portion of Bonriki–Taborio, Ambo–Teaoraereke, Nanikai and Bairiki), as for Fig. 5

Table 3 Summary of area changes for the two areas, and the entire atoll, over the 30-year period (1968–1998)

Sections	Initial (ha), 1968	Final (ha), 1998	Net area change (ha)	% change	Major reclamations (ha)	Natural changes and small developments (ha)
North Tarawa	1,489.42	1,528.54	39.13	2.63		39.12
South Tarawa	881.26	1,290.84	409.58	46.48	363.50	46.08
Total	2,370.68	2,819.38	448.70	18.93	363.50	85.2

Table 4 Major developments and their impact on reef island area

Development	Reef island	Area (ha)
Temaiku Bight reclamation	Bonriki–Taborio	335.00
Nippon Causeway	Betio and Bairiki	22.60
Betio Port	Betio	4.40
Reclamation	Ambo–Teaoraereke	1.50
Total		363.50

South Tarawa differ markedly from those in North Tarawa. These changes contribute a substantial proportion of the net accretion on the atoll (409.58 ha of the total 448.7 ha, or >91 %). The results show that six reef islands have undergone accretion, whilst two have remained stable. In descending order, the individual reef-island contributions are Bonriki–Taborio (348.14 ha), Betio (26.88 ha), Bairiki (17.21 ha), Ambo–Teaoraereke (14.31 ha), Nanikai (2.06 ha) and Abaokoro–South Tarawa (0.61 ha). The first five reef islands have high population densities of >20 persons/ha, and only Abaokoro is uninhabited (Table 6).

Further changes in South Tarawa are illustrated by a more detailed analysis of Bairiki. This reef island has a broad western end and elongated eastern end (Fig. 10), and is connected to adjacent reef islands by causeways. The reef island has a 1.8-km-long ocean coastline comprising mainly sandy shores with sections of 'seawalls' and conglomerate shorelines to the west. A total of 92 transects reveal that the pattern of change on the ocean side for both BB and VL shoreline indicators is accretion, at average rates of 0.4 and 0.5 m/year, respectively, with broadly similar trends for both. Shorelines experiencing accretion are situated on the sandy and artificial shorelines, mainly situated east of the conglomerate outcrop located about 0.6 km from Bairiki's western tip. The 1.7-km-long lagoon coastline comprises vegetated sandy, open sandy, artificial and beachrock shorelines. A protected artificial shoreline at the far west characterises the port, with outcrops of beachrock comprising lithified beach sand. There are also several small seawalls protecting a boat channel cutting across the reef flat to allow access at all tides. The 87 transects along the lagoon shore included 43 % stable, 39 % accreting and 18 % eroding for the BB metric (Fig. 10). On the other hand, the VL-based data showed 54 % accreting, 36 % stability and 10 % eroding. The maximum accretion rates are 1.3 m/year (BB) and 1.4 m/year (VL), and the maximum erosion rates are −1.8 m/year (BB) and −1.2 m/year (VL), both at the western end of the island. The correlation between BB and VL appears to be strong. The sandy beaches located just east of the port are very susceptible to erosion under El Niño westerly winds (Harper 1989). These results demonstrate the potential negative impact of coastal structures in areas where longshore sediment transport is predominant, particularly down-drift of structures.

The broad trends identified by the comparison of the 1968 and 1998 shorelines were further supported by longer term analysis involving the 1943 aerial photography and the 2007 satellite image. Five representative reef islands were selected to determine changes over the longer time scale of 64 years obtained from a time series of four shorelines: 1943, 1968, 1998 and 2007. The total coastline length investigated was 26.1 km, involving 1,233 transects. The LRR analysis in DSAS showed that rates of shoreline change observed over 64 years are similar to the 30-year results for both North Tarawa and South Tarawa; reef islands in North Tarawa have been stable, whereas those in South Tarawa have increased in area. As discussed above, the reef island expansion is largely due to human influence.

Discussion

Evidence of erosion of reef islands, including prominent scarps on beaches, undercutting of vegetation and the presence of outcrops of beachrock that formed when the beach was stable, has been used to infer that atolls are threatened by sea-level rise and that land may disappear on atolls as one of the first impacts of global warming (Woodroffe 2008). However, where detailed re-surveys of beaches have been undertaken, these trends have often been shown to be cyclic; for example, re-surveys of beach profiles on the reef islands of Betio and Buariki in South Tarawa indicate that fluctuations of island outline correspond with wind changes associated with inter-annual ENSO cycles (Solomon and Forbes 1999).

In the Gilbert Group, short-term variations in shoreline positions are related to periodic changes caused by ENSO.

Table 5 Physical and social characteristics of North Tarawa reef islands

Name/ID	Area (ha)		Net area change		Contribution to overall increase of atoll (%)	Status	Population density (persons/ha)
	1968	1998	ha	%			
Buariki	384.00	390.36	6.36	1.7	1.4	Accretion	3
Nuatabu	66.12	67.04	0.91	1.4	0.2	Accretion	3
3	1.65	1.54	−0.11	−6.8	−0.0	Stable	0
4	0.11	0.10	−0.02	−15.3	−0.0	Stable	0
Tebangaroi	65.96	70.87	4.91	7.4	1.1	Accretion	1
Taratai	172.66	177.62	4.96	2.9	1.1	Accretion	0
7	4.66	4.71	0.05	1.0	0.0	Stable	7
Notoue	113.33	119.96	6.63	5.8	1.5	Accretion	8
Abaokoro	28.26	32.64	4.38	15.5	1.0	Accretion	0
10	7.80	8.90	1.10	14.0	0.2	Accretion	1
Marenanuka	95.16	103.07	7.91	8.3	1.8	Accretion	8
18	0.64	0.50	−0.14	−22.2	−0.0	Stable	0
20	0.45	0.30	−0.14	−32.3	−0.0	Stable	0
23	1.10	1.02	−0.08	−7.3	−0.0	Stable	0
24	5.37	5.36	−0.00	−0.1	−0.0	Stable	0
25	2.02	1.94	−0.07	−3.6	−0.0	Stable	0
Kairiki	36.13	35.24	−0.89	−2.5	−0.2	Erosion	0
Kainaba	27.92	28.53	0.61	2.2	0.1	Accretion	9
29	3.43	3.44	0.01	0.3	0.0	Stable	0
30	0.23	0.17	−0.06	−26.6	−0.0	Stable	0
31	0.37	0.31	−0.07	−17.5	−0.0	Stable	0
32	0.58	0.38	−0.20	−34.0	−0.0	Stable	0
Bikenubati	11.48	11.35	−0.13	−1.1	−0.0	Stable	0
34	0.79	0.60	−0.19	−23.8	−0.0	Stable	0
36	0.47	0.40	−0.07	−14.3	−0.0	Stable	0
35	0.24	0.22	−0.02	−8.2	−0.0	Stable	0
37	0.20	0.17	−0.03	−13.7	−0.0	Stable	0
38	1.36	1.73	0.37	27.0	0.1	Stable	0
39	0.80	0.73	−0.07	−9.0	−0.0	Stable	0
Nea	14.49	14.27	−0.23	−1.6	−0.1	Stable	0
Biketawa	5.74	6.28	0.54	9.3	0.1	Accretion	0
Nabeina	36.42	36.25	−0.17	−0.5	−0.0	Stable	12
Tabiang	84.00	85.26	1.26	1.5	0.3	Accretion	0
Tabuki	32.24	31.24	−1.00	−3.1	−0.2	Erosion	0
Tabiteuea	103.53	104.49	0.96	0.9	0.2	Accretion	5
Abatao	79.83	80.19	0.36	0.5	0.1	Stable	6
Naninimai	4.71	4.65	−0.06	−1.3	−0.0	Stable	0
Buota	87.83	88.18	0.35	0.4	0.1	Stable	17
Tanaea	6.86	8.22	1.36	19.9	0.3	Accretion	34
51	0.48	0.33	−0.15	−31.3	−0.0	Stable	0
40	1,489.42	1,528.54	39.1	2.6	8.7		

Estimates of physical changes between 1968 and 1998, measured using the BB indicator

A large body of evidence as a result of SOPAC's coastal research work on South Tarawa establishes these seasonal fluctuations, highlighting ENSO's role in longshore sediment transport (Howorth 1982; Forbes and Hosoi 1995; Solomon and Forbes 1999). Beach profile studies over several years (Harper 1989), time-series of shoreline positions obtained from aerial photographs (Gillie 1993; Forbes and Hosoi 1995) and ground surveys (Forbes and Hosoi 1995) have contributed to this understanding. In South Tarawa, during normal conditions, the direction of sediment transport

Table 6 Physical and social characteristics of urban South Tarawa reef islands

Name/ID	Area (ha)		Net area change		Net area change by reclamation		Contribution of reclamation to atoll's net change	Status	Population density (persons/ha)
	1968	1998	ha	%	ha	%	%		
Bonriki–Taborio	514.78	863.19	348.41	67.7	335.00	96.2	74.7	Accretion	23
Betio	139.88	166.76	26.88	19.2	14.00	52.1	3.1	Accretion	94
Bairiki	42.01	59.22	17.21	41.0	13.00	75.5	2.9	Accretion	60
Ambo–Teaoraereke	167.13	181.44	14.31	8.6	1.50	10.5	0.3	Accretion	52
Nanikai	13.26	15.32	2.06	15.6		0.0	0.0	Accretion	64
Abaokoro–South Tarawa	2.38	2.99	0.61	25.8		0.0	0.0	Accretion	0
Tebwe	0.29	0.64	0.35	122.6		0.0	0.0	Stable	0
Abairaranga	1.54	1.28	−0.26	−16.8		0.0	0.0	Stable	0
	881.26	1,290.84	409.58	46.5	363.50	88.7	81.0		

Summary of physical changes between 1968 and 1998 measured using the BB indicator

Table 7 Estimates of changes to North Tarawa ocean shoreline position between 1968 and 1998, measured using the BB indicator

Name/ID	Length (km)	Number of transects (n)	Average Rates (m/year) (± 0.2)	Accretion (%)	Erosion (%)	Stable (%)	Status
Base of beach							
Tabiang	1.2	60	0.1	15	0	85	Stable
Kairiki	1.2	57	0.1	26	7	67	Stable
Kainaba	0.9	43	0.1	12	2	86	Stable
Tebangaroi	1.5	78	0.1	16	1	83	Stable
10	0.4	19	0.1	0	0	100	Stable
Marenanuka	1.7	58	0.1	10	0	90	Stable
Nuatabu	1.8	87	0.1	8	0	92	Stable
Nea	0.2	10	0.1	0	0	100	Stable
16	0.3	15	0	7	0	93	Stable
24	0.2	13	0	0	0	100	Stable
Buariki	6.3	296	0	10	5	85	Stable
Taratai	4.1	201	0	13	4	83	Stable
Notoue	2.3	111	0	11	5	85	Stable
Abaokoro	0.1	41	0	2	93	5	Stable
29	0.2	8	0	0	0	100	Stable
Bikenubati	0.5	22	0	5	0	95	Stable
Tabiteuea	2.2	103	0	0	0	100	Stable
Abatao	1.7	74	0	0	0	100	Stable
Tanaea	0.3	20	0	25	20	55	Stable
3	0.1	3	−0.1	0	100		Stable
Nabeina	0.5	26	−0.1	0	0	100	Stable
Tabuki	0.7	32	−0.1	0	3	97	Stable
Buota	1.5	69	−0.1	1	6	93	Stable
25	0.1	6	−0.2	17	66	17	Stable
Biketawa	0.4	23	0.5	61	26	13	Accretion
38	0.1	6	0.4	50	0	50	Accretion
Total	30.5	1481					

Status of shoreline is defined using average rates of change. Accretion is >0.2 m/year, stable being ±0.2 m/year and erosion <−0.2 m/year

is westward, resulting from prevailing easterly winds and associated incident waves (Harper 1989). During La Niña conditions, the strength of the easterly winds is enhanced. In contrast, under El Niño conditions, the predominant easterly winds and related waves are weakened, leading to a reversal of the sediment transport direction.

On Tarawa, foraminifera are a major component of the sediments both on reef flats and in the lagoon (Weber and Woodhead 1972), and the tests of *Amphistegina* and *Baculogypsina* are particularly abundant in the sediments of reef islands. Radiocarbon dating of samples of foraminifera collected from pits across transects on several reef islands

Table 8 Estimates of changes to lagoon shoreline position on North Tarawa reef islands between 1968 and 1998, measured using the BB indicator

Name/ID	Length (km)	Number of transects (n)	Average rates (m/year) (±0.2)	Accretion (%)	Erosion (%)	Stable (%)	Status
Base of beach							
Abaokoro	0.5	28	0.2	53	4	43	Stable
Taratai	4.1	200	0.2	41	9	50	Stable
Nabeina	0.4	25	0.1	36	60	4	Stable
Buariki	7.4	360	0.1	27	10	63	Stable
Kairiki	0.7	33	0.1	15	3	82	Stable
24	0.1	3	0.1	67	33	0	Stable
Tanaea	0.1	4	0.1	0	25	75	Stable
Abatao	1.7	86	0.1	15	0	85	Stable
Tabiteuea	2.8	142	0.1	33	15	52	Stable
Tabuki	1.0	51	0.1	12	82	6	Stable
29	0.1	10	0	10	70	20	Stable
Bikenubati	0.1	21	0	10	85	5	Stable
17	0.4	19	0	11	6	83	Stable
Nuatabu	1.6	74	0	22	56	22	Stable
Nea	0.2	13	0	15	8	77	Stable
Buota	1.1	60	−0.1	18	62	20	Stable
Kainaba	1.0	54	−0.1	4	24	72	Stable
Tabiang	1.7	74	−0.1	12	69	19	Stable
Biketawa	0.5	24	−0.1	29	46	25	Stable
Marenanuka	2.6	125	0.5	55	3	42	Accretion
Notoue	3.3	145	0.4	62	32	6	Accretion
25	0.1	5	0.3	50	0	50	Accretion
Tebangaroi	1.5	72	0.3	40	20	40	Accretion
Total	33.0	1,628					

Status of shoreline is defined using average rates of change. Accretion is >0.2 m/year, stable being ±0.2 m/year and erosion <−0.2 m/year

in North Tarawa indicates that they have formed over the past 4–5 millennia as calcareous reef sediments have accumulated primarily on the oceanward shores, in a similar manner to the radiocarbon-dated reef island accretion history determined on Makin to the north (Woodroffe and Morrison 2001). Such sediments are still produced on the reef flat and in the lagoon. The continued production of carbonate sediment by reef biota would appear to supply sand that could still be incorporated into reef island building. Such processes provide mechanisms for the natural growth of reef islands, as envisaged by Webb and Kench (2010), and presumably contribute to the observed accretion on neighbouring atolls (Rankey 2011). The increases in area of reef islands in North Tarawa likely represent such natural additions of skeletal sand to the reef islands. However, Ebrahim (2000) suggested that human activities in South Tarawa, particularly eutrophication of shallow-marine habitats around densely settled reef islands, has reduced the production of, and in some cases deformed, these foraminifera. This, in turn, has decreased the supply of sediment to build those reef islands.

Webb and Kench (2010) implied that reef islands in the central Pacific are naturally growing because of net accretion, and, in particular, reef islands on Tarawa are growing faster than average. Their study took little account of the inter-annual variations in shoreline position associated with ENSO or the role that humans have played. Although they discuss that the observed shoreline changes on these urban reef islands occurred during a period when human activity was high, the conclusion they reached does not incorporate the numerous reclamations in South Tarawa, such as the port in Betio. Reclamations and seawalls have contributed by adding more land to the reef islands, especially on the ocean side, as indicated by the high rates of accretion. The negative impact of this human activity is that protruding structures such as the port in Bairiki have blocked longshore sediment transport to the east during El Niño periods, leading to acute erosion, resulting in the loss of several houses (Solomon and Forbes 1999). Stricter policies relating to coastal structures such as reclamations and seawalls need to be established. Such structures should accommodate longshore transport so that sediment pathways are not disrupted. In many instances, solid structures such as causeways and groynes should be discouraged.

The mapping of shoreline changes around Tarawa Atoll described here shows that reef islands have, indeed,

Table 9 Estimates of changes to ocean and lagoon shoreline positions on urban South Tarawa reef islands between 1968 and 1998, measured using the BB indicator

Name	Length (km)	Number of transects (n)	Average rates (m/year) (±0.2)	Accretion (%)	Erosion (%)	Stable (%)	Status
Ocean							
Ambo–Teaoraereke	5.2	298	0.1	22	9	69	Stable
Bonriki–Taborio	3.6	857	−0.1	3	17	80	Stable
Abairaranga	0.2	7	−0.2	0	14	86	Stable
Bairiki	2.6	92	0.5	79	7	14	Accretion
Nanikai	1.2	62	0.5	10	16	74	Accretion
Abaokoro–South Tarawa	0.2	6	0.4	50	0	50	Accretion
Betio	4.3	182	0.3	49	10	41	Accretion
Total	17.3	1,504					
Lagoon							
Ambo–Teaoraereke	5.3	279	0.2	44	9	47	Stable
Bonriki–Taborio	10.7	670	0.2	29	11	60	Stable
Bairiki	1.7	87	0.1	39	18	43	Stable
Abairaranga	0.1	5	−0.1	0	20	80	Stable
Nanikai	1	56	−0.1	11	39	50	Stable
Abaokoro–South Tarawa	0.1	5	−0.2	0	20	80	Stable
Betio	3.6	180	0.5	64	2	34	Accretion
Total	22.5	1,282					

Status of shoreline is defined using average rates of change. Accretion is >0.2 m/year, stable being ±0.2 m/year and erosion <−0.2 m/year

increased in area by 448.7 ha over the past three decades. Nonetheless, it also reveals that human activities on the reef islands of urban South Tarawa account for >90 % of this increase, with 363.5 ha out of 409.6 ha being the result of major reclamations. Temaiku Bight, on the southeastern corner of the lagoon, contributed a substantial 335 ha to Bonriki–Taborio reef island, accounting for most of this total. Much of the rest is related to shore protection or local reclamations. Similar reports of reef island area increase have been observed on urban Majuro, in the Marshall Islands, again mainly related to human activity (Ford 2012). Interventions, such as protruding reclamation structures, have further deleterious effects, firstly by removing sediment from surrounding areas for fill material and secondly by blocking longshore sediment transport, leading to erosion, as observed in urban Majuro (Ford 2012).

Fewer changes were anticipated around North Tarawa reef islands due to human activity because of the low population density. These reef islands have been predominantly stable over the past few decades. Relatively few areas experienced accretion; rates >0.2 m/year occurred only locally, in areas such as embayments, sand spits and beaches facing inter-island channels. Similar patterns and rates of accretion have been measured for Maiana ocean shores for the period between 1969 and 2009 (Rankey 2011), with accretion in embayments and on sand spits. However, not all accretional changes appeared to be natural, as lagoonal sandy beaches adjacent to causeways in North Tarawa were probably related to human activity, a similar situation to the accreting beaches close to the causeways in South Tarawa (Forbes and Biribo 1996). Only some areas are affected by human activity, especially where causeways are built between the reef islands.

Beach mining, whether part of major developments or local family-scale collection of beach shingle following high spring tides, should be prohibited in proximity to settlements, as it is not a sustainable activity. Alternative options for aggregate supply need to be explored which do not directly affect the beaches. These include purchasing aggregate from overseas, which has been done in the past (Geer Consulting Services 2007), or supplying aggregate from the recently established state-owned enterprise Atinimarawa Company Ltd (ACL), which plans to extract materials from the lagoon. The ACL needs to meet the local demands at a cheap price to stop locals from mining the beaches (Geer Consulting Services 2007). One of the proposed options of this project is to encourage people who depend on the sales of aggregate to become retailers for the company (Leney 2012). This is considered important, as 38 % of the households in Bonriki and Temaiku villages depend on aggregate sales as their main income. Doing this will ensure that these people do not lose their income, as well as stopping mining activities on the beaches

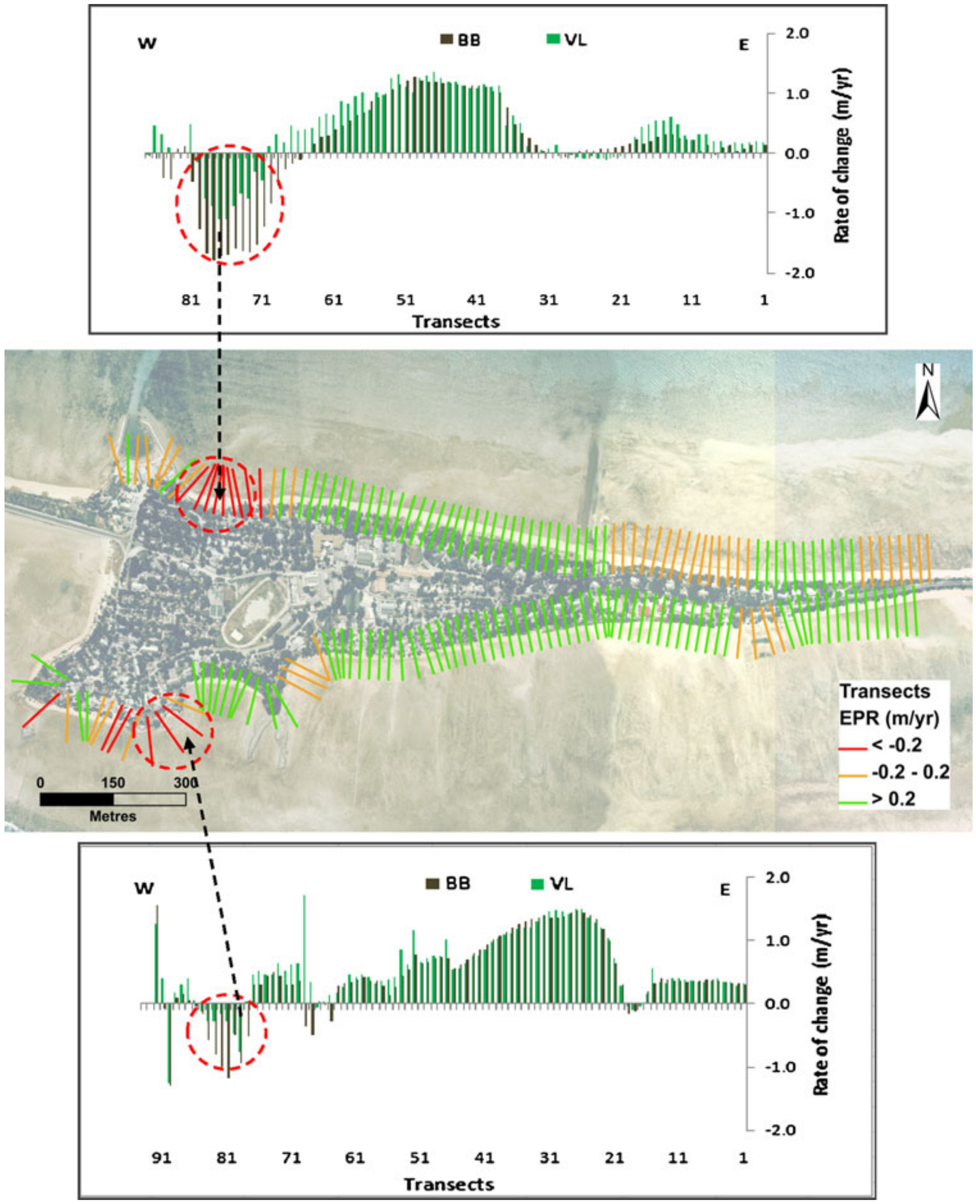

Fig. 10 Shoreline changes around Bairiki from 1968 to 1998 showing the rates of change along the lagoon shore (*above*) and ocean shore (*below*), by both the base of the beach (BB, in *black*) and vegetation line (VL, in *green*) indicators. The *red circles* mark some areas of substantial erosion that occur in areas which have been modified by humans

(Peletikoti 2007). Economic analysis shows that the amount of aggregates in the Vinstra Shoal, located in the lagoon north of Betio, is insufficient, meeting only half of the local demands. Major developments will need to source their materials from overseas, to enable the lagoon supply to be extended beyond the 50-year lifetime of the deposit (Geer Consulting Services 2007). Other options may include using alternative construction materials, such as prefabricated material, and constructing two-storey buildings. The latter may also assist in reducing the extent of reclamations.

As the sea level rises in the future, the maintenance of reef island area will require that neither the supply nor the pathways of transport of sediments to the reef islands be reduced. Continued monitoring of sediment and shoreline behaviour will be important to reduce the vulnerability of reef islands under anticipated accelerated rates of sea-level rise in the future. Repeated studies need to provide a foundation for appropriate adaptation measures to increase the resilience of reef islands, recognising coastal processes and variability associated with ENSO, and limiting the construction of coastal structures, as they have more negative than positive impacts.

Conclusions

Despite the widely held perception that reef islands around the perimeter of coral atolls are eroding and will disappear as a consequence of sea-level rise resulting from global warming, this study shows that the total area of reef islands on Tarawa Atoll has increased over recent decades. The increase, however, is, overwhelmingly, an outcome of human activities and is dominated, in particular, by extensive reclamations. More than 360 ha of the approximately 450 ha by which the total atoll land area increased from 1968 to 1998 is the result of the major reclamation project on Bonriki–Taborio and construction projects on Betio and Bairiki.

Calcifying organisms, from which the sediments are derived, still live on the reef flats and in the lagoon at Tarawa, but the rate of production, particularly of foraminifera, may have decreased adjacent to the most densely settled reef islands. Accretion of these sediments which have built the reef islands over past millennia, particularly on ocean-facing beaches but also on lagoon shores, can be inferred at barely detectable rates in North Tarawa. However, slower rates for South Tarawa are overwhelmed by the consequences of human activities over recent decades. Contrary to the concept of naturally resilient reef islands that could be inferred from the conclusion of Webb and Kench (2010) that Pacific atoll reef islands are growing, increases in area attributed primarily to human activities are less sustainable into the future as the sea level rises. As the number of people has increased on the most heavily urbanised atoll reef islands, increases in island area have been driven by reclamation, which has far exceeded the modest natural rates of accretion, and, in many cases, if not all, has disrupted pathways of sediment movement. With increasing population pressures and development, more encroachment onto the active beach will result in further interruptions to longshore sediment transport.

The rate of island area change at a longer time scale of 64 years on five reef islands of North and South Tarawa was comparable to the 30-year results. Reef islands of North Tarawa show stability or slight increase in area, apparently related to natural processes, as the reef islands have low population density and little development. Accretion and erosional changes occur in localised areas such as embayments, beaches near closed channels, sand spits and beaches facing inter-island channels. Human activities are more evident than natural change on South Tarawa, and longshore sediment movement on South Tarawa is influenced by ENSO variability, which modifies the magnitude and direction of transport. This variability has other effects, such as widespread erosion adjacent to disjointed reclamation structures.

The results of this study may be applicable to reef islands on other atolls in the Pacific, discriminating those reef islands where natural processes continue to dominate, such as Maiana, from urbanised reef islands that have been largely influenced by human activity, such as Majuro in the Marshall Islands. Gradual sea-level rise over the past decades is likely to have begun to influence patterns of shoreline change, with different impacts depending on whether parts of reef islands are eroding, remaining stable or accreting. Complex patterns of erosion and accretion are likely to continue in the future as the sea rises further, with flooding of low-lying areas becoming more frequent and natural rates of sediment accretion contributing less to the expansion of reef islands as the sea level continues to rise. Creating land, or extending reef island shorelines, whether by expensive engineering projects or ad-hoc local activities, will become increasingly unsustainable into the future under almost any scenario. Not only are there constraints on the availability of suitable aggregate, but there are adverse environmental consequences in adjacent areas, whether in the nearshore lagoon borrow-pit areas or on adjoining sections of coastline. Concerted efforts to reduce the damaging impacts of human activities will be needed, along with education programmes to promote the sustainability of reef islands, forbidding the extraction of sand aggregate from beaches in close proximity to settlements and mitigating alongshore effects of any structure that is built on the shoreline. Coastal structures such as reclamations and seawalls should be carefully considered, as they negatively affect the sediment dynamics by removing sediment and blocking longshore sand transport. In conclusion, coastal managers on reef islands on Pacific atolls need to reduce the negative impacts of human activities and promote further resilience on already dynamic shorelines.

Acknowledgments This study was undertaken during tenure of an AusAID scholarship by N.B. We are grateful to Schlencker Mapping for access to the photography and photogrammetry; we appreciate the support of the Government of Kiribati. Radiocarbon age analyses were undertaken under Grant AINGRA10073 from the Australian Institute of Nuclear Science and Engineering (AINSE). We appreciate the constructive comments from the reviewers and editors of this special issue.

References

Australian Bureau of Meteorology and CSIRO (2011) Climate change in the Pacific: scientific assessment and new research

Boak EH, Turner IL (2005) Shoreline definition and detection: a review. J Coast Res 21:688–703

Burne RV (1983) Origin and transportation of beach sand, Betio-Bairiki, Tarawa, Kiribati. SOPAC Technical Report CR0081, 79 pp

Byrne G (1991) Sediment movement on Tarawa, Kiribati. In: Workshop on coastal processes in the South Pacific Island Nations, Lae, Papua New Guinea, October 1987. SOPAC Technical Bulletin, vol 7, pp 155–159

Donner S (2012) Sea level rise and the ongoing Battle of Tarawa. EOS 93:169–176

Ebrahim MT (2000) Impact of anthropogenic environmental change on larger foraminifera: Tarawa Atoll, Kiribati, South Pacific. In: Martin RE (ed) Environmental micropaleontology: the

application of microfossils to environmental geology, vol 15. Kluwer, New York, pp 105–117
Forbes DL, Biribo N (1996) Shore-zone sand and gravel of South Tarawa, Kiribati: preliminary assessment of selected sites. SOPAC Technical Report 235, 45 pp
Forbes DL, Hosoi Y (1995) Coastal erosion in South Tarawa, Kiribati. SOPAC Technical Report 225, 92 pp
Ford M (2012) Shoreline changes on an urban atoll in the central Pacific Ocean: Majuro Atoll, Marshall Islands. J Coast Res 28:11–22
Geer Consulting Services (2007) Kiribati Technical Report: Economic analysis of aggregate mining on Tarawa. Reducing Vulnerabilty of Pacific ACP States 71:1–112
Gillie RD (1993) Historical changes of shoreline accretion and erosion Betio Islet, South Tarawa, Kiribati. SOPAC Technical Bulletin 179, 21 pp
Harper JR (1989) Evaluation of beach profile data from Betio and Bairiki, Republic of Kiribati, 1982–1988. SOPAC Technical Report 94, 136 pp
Howorth R (1982) Technical report on coastal erosion in Kiribati; visit to South Tarawa 22 January–10 February, 1982. SOPAC Technical Report 22, 61 pp
Kench PS, Cowell PJ (2002) Erosion of low-lying reef islands. Tiempo 46:6–12
Kinsey DW, Hopley D (1991) The significance of coral reefs as global carbon sinks—response to Greenhouse. Palaeogeogr Palaeoclimatol Palaeoecol 89:363–377
Leney A (2012) Analysis of the socio-economic impacts of the ESAT program, and mitigation measures being taken to minimise any adverse impacts on the community of South Tarawa, Bairiki, Tarawa, 15 pp
Marshall JF, Jacobson G (1985) Holocene growth of a mid-Pacific atoll: Tarawa, Kiribati. Coral Reefs 4:11–17
McLean RF (2011) Atoll Islands (Motu). Encyclopedia of modern coral reefs: structure, form and process. Springer, The Netherlands, pp 47–51
Mimura N (1999) Vulnerability of island countries in the South Pacific to sea level rise and climate change. Clim Res 12:137–143
Ministry of Finance and Economic Planning (2010) 2010 census of population. Ministry of Finance and Economic Planning, Bairiki, Tarawa
Morton RA, Miller HL, Moore LJ (2004) National assessment of shoreline change: part 1, historical shoreline changes and associated coastal land loss along the U.S. Gulf of Mexico. USGS Open File Report 2004-1043
Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. In: Parry ML, Canziani OF, Palutikof JP, van der Linden P, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 315–357
Patel SS (2006) Climate science: a sinking feeling. Nature 440:734–736
Peletikoti N (2007) Kiribati Technical Report: 1) Extent of Household Aggregate Mining in South Tarawa; and 2) Proposed Integrated Monitoring Framework for Tarawa Lagoon EU EDF8 SOPAC Project Report 72, 70 pp
Ramsay DL, Stephens S, Gorman R, Oldman J, Bell R, Damalmian H (2010) Sea levels, waves, run-up and overtopping. Kiribati Adaptation Programme. Phase II: information for climate risk management. NIWA Ltd., Hamilton, 148 pp
Rankey EC (2011) Nature and stability of atoll island shorelines: Gilbert Island chain, Kiribati, equatorial Pacific. Sedimentology 58:1831–1859
Richmond BM (1992) Development of atoll islets in the central Pacific. In: Proceedings of the 7th International Coral Reef Congress, Guam, Micronesia, June 1992, vol 2, pp 1185–1194
Richmond BM (1993) Reconnaissance geology of the Gilbert Group, Western Kiribati. SOPAC Technical Report 77, 64 pp
Sheppard C, Dixon DJ, Gourlay M, Sheppard A, Payet R (2005) Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. Estuar Coast Shelf Sci 64:223–234
Solomon S (1997) Assessment of the vulnerability of Betio (South Tarawa, Kiribati) to accelerated sea level rise. SOPAC Technical Report 251, 66 pp
Solomon SM, Forbes DL (1999) Coastal hazards and associated management issues on South Pacific Islands. Ocean Coast Manag 42:523–554
Terry JP, Chui TFM (2012) Evaluating the fate of freshwater lenses on atoll islands after eustatic sea-level rise and cyclone-driven inundation: a modelling approach. Global Planet Change 88–89:76–84
Thieler ER, Himmelstoss EA, Zichichi JL, Ergul A (2009) The Digital Shoreline Analysis System (DSAS) version 4.0—an ArcGIS extension for calculating shoreline change. USGS Open-File Report 2008-1278, 79 pp
Webb AP, Kench PS (2010) The dynamic response of reef islands to sea-level rise: evidence from multi-decadal analysis of island change in the central Pacific. Global Planet Change 72:234–246
Weber JN, Woodhead PMJ (1972) Carbonate lagoon and beach sediments of Tarawa Atoll. Atoll Research Bulletin 157, 31 pp
Woodroffe CD (2008) Reef-island topography and the vulnerability of atolls to sea-level rise. Global Planet Change 62:77–96
Woodroffe CD, Morrison RJ (2001) Reef-island accretion and soil development on Makin, Kiribati, central Pacific. Catena 44:245–261
Yamano H, Kayanne H, Yamaguchi T, Kuwahara Y, Yokoki H, Shimazaki H, Chikamori M (2007) Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. Global Planet Change 57:407–416