STABILITY OF ATOLL ISLAND SHORELINES:
REPUBLIC OF KIRIBATI

Dr. Gene Rankey
Department of Geology
University of Kansas
120 Lindley Hall
Lawrence, KS 66045
grankey@ku.edu

With contributions by:
Daniel Doolittle
Puta Tofinga
Tion Uriam
Kabure Yeeting

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EXECUTIVE SUMMARY

Coastlines, at the interface between land and sea, are dynamic systems. They can be impacted by many factors, including tides, waves, winds, climatic effects, storms, and humans. The objective of this study was to map and understand controls on changes on islands of atolls in the Republic of Kiribati. To accomplish this goal, this study systematically mapped and analyzed field, laboratory, and remote sensing data from islands on Aranuka and Maiana atolls. Results indicate:

1. Islands in Kiribati include sandy, rocky, and mangrove shorelines. All are changing.
2. The direction of change is variable; some shorelines are erosional, some accretionary.
3. On longer time scales (1969-2009), both the oceanward and the lagoonal shorelines of Maiana are accretionary (mean rates of just over 0.0 and +0.2 m/yr, respectively) (here and after, positive rates refer to accretion, negative rates refer to erosion).
4. Between 2005 and 2009 on Maiana, trends diverge; oceanward shorelines are accretionary (mean rate of +0.3 m/yr), whereas lagoonal shorelines are erosional (mean rate of -0.2 m/yr). Trends on Aranuka are broadly similar, with ocean shorelines stable to accretionary (mean rate +0.0 m/yr) and lagoonal shores indicating net erosion (mean rate of -0.2 m/yr) during this period. Recent patterns on sandy islets on Aranuka and Maiana atolls suggest net erosion (mean rates of -0.0 m/yr and -0.1 m/yr, respectively).
5. At any one location, the nature and rate of change can be variable through time. In some areas, long-term trends (1969-2009) are opposite (e.g., erosion versus accretion) short-term trends (2005-2009). Rates of shoreline change on both atolls are greater between 2005-2009 than between 1969-2009.
6. The most dynamic parts of the large windward islands on these atolls are near their termini.
7. Many village shores are changing; this relation is in many cases related to building groins, which drive local erosion and accretion.
8. Most shorelines are dominated by longshore transport. In general terms, the transport on the oceanward sides of the larger, windward islands is towards the north and south ends of the islands, away from the island center. On the lagoonal shores, most observations from Maiana indicate net southward transport all along the length of the island, whereas evidence from Aranuka suggests net northward transport.
9. Rocky outcrops play an important role in coastal processes because they inhibit erosion and modify longshore patterns.

The islands of Kiribati nucleated several 1000 years ago on exposed reefal deposits (now observed as the rocky outcrops), raised above sea-level by a relative fall in sea level. The trends in location of erosion and accretion observed in the last 4 years are broadly consistent with their being largely influenced by "normal" (La Nina) tradewinds. Recent increases in the rate of change of shorelines on the islands may simply reflect short-term 'noise,' or they may be the manifestation of an increased rate of sea-level rise or climate change. Distinguishing between these two possibilities and evaluating the role of El Nino-Southern Oscillation (ENSO) variability will require continued monitoring and study of these and other atolls.
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Introduction

Tropical islands and their coastlines are dynamic systems, responsive to many factors, including global change (McLean and Stoddart, 1978; Richmond, 1993; Yamano et al., 2005; Kench and Brander, 2006). Although there is general agreement that relative change in sea-level will influence coastlines, considerable debate remains concerning the nature, rates, and even causes of morphologic change on tropical islands. For example, Woodroffe (2008, p. 94) suggested that “oceanward shores [of islets] are often accretionary, although localized evidence of erosion may persist.” In stark contrast, Dickinson (1999, p. 124) noted historical erosion and commented that “future sea level rise...might trigger enhanced wave erosion of stable atoll islets.” Questions of the nature, rates, and causes of island change are of more than academic interest - with recent increases in the rate of sea-level rise, as anecdotal evidence suggesting erosion mounts, coastline dynamics have become a central concern for many small, low island nations (Roy and Connell, 1991; Barnett and Adger, 2003). Yet, as noted by Kench and Brander (2006) “studies of atoll island change are scarce.”

The Republic of Kiribati, a series of low islands, is a nation at the “front lines of global change.” As a whole, this equatorial nation includes 33 atolls, with a land area of just over 800 sq km. Most of the islands are several 100 m wide, and no more than 3 - 4 m above sea level. Anecdotal evidence and several recent studies suggest that at least parts of many of the islands are eroding, perhaps in response to sea-level rise. Yet, as many island residents are displaced, President Anote Tong notes, “We cannot move further inland due to the narrowness of our islands nor are their higher grounds to which we could escape the rising seas....” (address to the United Nations General Assembly, 25 September, 2008).
As a starting point for developing a quantitative understanding on the nature and causes of change on atoll islands, this project collected and analyzed remote sensing data (to explore how islets have changed from the last El Nino to present La Nina phase) in the context of in situ field observations on atolls with a range of islet orientations and settings. In general terms, the project aimed to answer fundamental questions, including:

- Are shorelines changing? If so, how rapidly?
- How do rates of change vary, spatially and temporally?
- What controls these changes?

The implicit approach used in this study is that the possible role of controlling variables can be best evaluated by studying a comprehensive suite of shorelines of different orientations and settings, all around several atolls. This approach differs from many previous studies in Kiribati that have tended (rightly, given their mandate) to focus on densely populated areas (e.g., Forbes and Hosoi, 1995; He, 2001). As such, in focusing on general concepts rather than specific locations, this report includes no specific results or recommendations for any particular village or area.

This report, prepared for the Ministry of Fisheries and Marine Resources Development as status update, represents the first documentation of an on-going project. Please contact Dr. Gene Rankey (granky@ku.edu) with any questions or comments.

**Setting**

*Location & Geography*

The Gilbert Island chain of the Republic of Kiribati straddles the equator in the west-central Pacific, centered at longitude 174E. This NW-SE trending chain of 11 atolls and five reef islands rises from oceanic floors ~4000 m deep, of Cretaceous-Jurassic age (Richmond, 1993). The atolls, two of which (Maiana and Aranuka; Figure 1) are the focus of this report, share many general geomorphic characteristics. Most are elongated NW-SE, with a well-developed reef rim, rocky intertidal reef flat, and sandy islands on their eastern, windward margin. Western, leeward margins are less fully aggraded, and many remain submerged, even at low tide; islands are very rare on these margins. The lagoons of atolls are shallow, ranging from <10 m to >25 m. Aspects of the general Holocene geology and evolution of islands in this chain have been described by Cloud (1952), Richmond (1993), and Woodroffe and Morrison (2001).

*Oceanography and Climate*

Rainfall is highly variable in the Gilbert Island chain. The northern islands (such as Butaritari, Makin) are generally wetter, receiving in excess of 250 cm average rainfall annually. Rainfall decreases to the south however, and many of the islands in the southern part of the Gilbert
Islands are characterized by <120 cm annual rainfall. Maiana and Aranuka, the focus of this study, lie in the middle, with ~150-200 cm average annual rainfall.

Because of its equatorial position, most of Kiribati is not directly impacted by tropical cyclones (only one, from 1927 or 1928 has been recorded, in the northern Gilbert chain) or pronounced seasonal shifts or cold fronts. Much of the Gilbert Island chain lies in the easterly trade-wind belt, and “normal” winds are from the east. In Kiribati and the equatorial Pacific, however, one dynamic that might significantly influence coastal dynamics is El Nino/Southern Oscillation (ENSO) variability. Between El Nino and La Nina phases, winds switch direction and strength (Carter, 1983; Figure 2), and sea level changes as well (National Tidal Centre, 2009). As described above, climate during the 2005-2009 focus period shifted from a La Nina phase to a neutral phase, and presently (January 2010) an early El Nino phase (Figure 2; NOAA, 2009).

The change in wind direction and intensity associated with ENSO variability also influences waves (Carter, 1983). Winds during La Nina phases (e.g., most of the 2005-2009 period) represent the “normal” moderate tradewinds from the east, which generate waves with short period (>6 s) and small significant wave height (<2 m). In contrast, El Nino phases are characterized by more variability in direction (winds from both the west and the east), and generally stronger winds. These stronger El Nino winds can generate offshore waves with greater period (>10 s) and significant wave height (>5 m). Waves in the lagoon are smaller, although Carter (1983) suggested that significant wave height of 2 m might occur here “at least once in 50 years.”

Tides in Kiribati are semi-diurnal. Spring tidal amplitude can exceed 2 m. Likewise, data from Tarawa (summarized in Solomon, 1997) suggest that sea level also varies 40 cm with ENSO shifts (higher during El Nino phases), and even seasonally, related to variations in the strength of ocean currents. The higher sea-levels and larger waves during El Nino phases likely have a marked impact on shorelines.

Methods

To better understand the nature and changes of Kiribati shorelines, this study utilized and integrated several types of data including remote sensing and aerial imagery, differential GPS measurements of shoreline position and elevation, and field and laboratory sedimentologic characterization. Each observation was placed in a spatial context for analysis using a GIS. The general workflow is illustrated in Appendix 2.

Prior to field work in Kiribati, remote sensing images from 2005-2009 from Maiana and Aranuka atolls were examined and compared. This preliminary analysis suggested different shoreline types, and highlighted areas with apparent stability during this period, and other areas with marked change in shoreline position (documented below). The strategy for field work focused on exploring shorelines spanning the diversity of locations (oceanward, lagoonward), orientations (e.g., northeast facing, southeast facing), characteristics (rocky, sandy, mangrove), and stability (no evidence for change, marked evidence for change).

Within this framework, field observations (participants highlighted in Figure 2B) included collection of DGPS data of shoreline location and elevation at 12 focus sites, six on both Maiana and
Aranuka. In each area, data collected from several (6-12) transects normal to the shoreline characterize the height and slope of beaches, and mapping of the toe of the beach (ToB; Kench and Brander, 2006) constrain beach location. Several possible positions were evaluated in the field as mappable references (vegetation line, scarp, toe of beach), but mapping the ToB was adapted as a practical matter, for two key reasons: 1) it was always present, distinct and easily mappable in the field, unlike the vegetation line or beach berm, and the ToB had fewer DGPS reception issues than the vegetation line; and 2) it was objectively mappable on all imagery data sets, because it was not obscured by vegetation. Nonetheless, the position of the vegetation line was mapped in a few areas, but only as time permitted. Collectively, these DGPS data include >20,000 measurements. These data will become more valuable in time, as a baseline for observing the details of change.

In the field, in addition to collection of DGPS data, the sedimentologic and geomorphic character of the shorelines was noted in each focus area and in several other illustrative regions. In focus areas, a representative suite of sediment samples were collected (at a minimum) at the top of the beach, midway up the beach profile, at the toe of the beach, and “offshore.” Rocky outcrops were described, and samples were collected for petrographic analysis.

Because of their high positional accuracy, these data were used to georectify the most recent (2009) QuickBird or WorldView high-resolution images, which then formed the basis for rectifications for the earlier (2005-2006 QuickBird) data. For Maiana, aerial photos from 1969 were available; these were georectified to the 2009 data. The WorldView data have pixels of 0.5 m², whereas the QuickBird data include panchromatic data of 0.6 m² and multispectral data of 2.4 m². Details are found in Appendix 1.

Within the context of the calibrations provided by field observations and DGPS data, the position of the shoreline was manually digitized using ERMapper around the entire island from a 2009 image, a 2005 image, and (for Maiana) 1969 aerial photos. In addition to defining its location, the character of the shoreline (rocky, mangrove, sandy, sandy-rock; see below) was interpreted from the remote sensing imagery.

Subsequent analyses focused on capturing the amount and nature of change. To capture this, older (2005 and 1969) shorelines were converted to points at 10 m spacing (5,620 points for 2005 Aranuka shore, 10,424 points for 2005 Maiana shore; 9,912 points for 1969 Maiana shore). The distance from these points to the 2009 shoreline was measured, and the class of 2009 shoreline was also captured (e.g., for comparison). These data were then analyzed in ArcGIS and statistical analysis programs.

**Island Geomorphology: Aranuka and Maiana Atolls**

As is common in the Gilbert Island group, the largest islands of Aranuka and Maiana atolls occur on their eastern, windward margins. These large islands are narrow (mostly < 1500m), and broadly arcuate in shape, curving from northeast-facing to southeast-facing. Following Woodroffe (2008), in this report, oceanward shores refer to those that fall around the atoll perimeter facing the open ocean, and lagoonward shores are those that face the shallower lagoon. The windward margins of both islands are flanked by rocky reef platforms, broad (~300 m wide on Aranuka; ~175-400 m
wide on Maiana), flat cemented rocky surfaces largely barren of living corals, but with sparse small patches of thin, irregular skeletal sands. The reef platforms are intertidal, and exposed at low tide. To the lee (west) of Maiana island, a 500-1000 m-wide sandy intertidal flat runs the length of the island. In contrast, Aranuka island has few comparable lagoonward sandy flats; instead, water depths increase offshore, such that a few 10s-100 m from the shore, the seafloor is wholly subtidal, with marine benthos and seagrass. Exceptions occur at the southwest end of the island, where it abuts a sandy to rubble shallow subtidal to intertidal reef flat with live reefal growth, and at the north end, where a "hook" partly encloses a broad intertidal flat.

Representative topographic transects of Maiana and Aranuka islands (Figure 3) show trends broadly similar to that described on other Gilbert chain islands (Cloud, 1952; Richmond, 1993; Woodroffe and Morrison, 2001) On each island, the oceanward shore steeply slopes up to the highest ridge on the island, reaching up to ~3.5 m above the reef platform on Maiana, and 3.2 m on Aranuka. The surface slopes gradually down from this high ridge to a central depression. In many areas, this depression includes numerous pits, used to grow taro. The islands increase in elevation from this central low up to the lagoonal shoreline, before dipping into the atoll lagoon.

With a large island on its leeward margin, Aranuka is unique of the atolls of Kiribati. The island, Tekaeang, reaches up to 1.6 x 5.5 km, is elongated east-west and is surrounded on three sides (north, west, south) by a 250-900 m wide intertidal reef platform. The western, northern, and southern margins of the island includes several generations of progradational beach ridges, each separated by erosional truncations (Richmond 1993) (Figure 1, inset). Collectively, these ridges shape the island, form a westward facing U-shape. The east side, facing into the lagoon, forms a broadly triangular shoreline narrowing to the east, and is flanked to the north and south by a broad sandy rippled intertidal flat that can exceed 1000 m width before passing outboard to the rocky reef platform. The change in character (from U-shaped flanking the reef platform to the tapering west end and the western sand flat) is coincident with the position of rubble ridges that extend roughly north-south from the island, features which have been interpreted (Richmond, 1993) to act as groins.

**Shoreline Classes**

Based on the nature of the substrate and vegetation, the shorelines of the atolls of Maiana and Aranuka can be broadly grouped into five general classes: rocky–rubble, rocky-bedded, sandy-rock, mangrove, and sandy (Table 1; Figure 4). The sandy and mangrove shoreline types are characterized by sandy foreshores (Figure 4A) and mangrove forests (Figure 4B), respectively. The rocky-rubble shorelines generally consist of massive, non-bedded (Figure 4C) coral-red algal sand to cobble conglomerate to boundstone (in situ growth) that commonly has a shore-normal outcrop form (Figure 4D). In marked contrast, the rocky-bedded shorelines include finer grains (sand-pebble), distinct oceanward-dipping bedding (Figure 4E), obvious physical sedimentary structures, and (commonly) an along-shoreline outcrop form. Nonetheless, there appears to be a spectrum between these two end-members, and without ground validation, it is difficult to distinguish between rocky-rubble and rocky-bedded from the remotely sensed data. For mapping purposes, therefore, these classes were lumped. Because they appear genetically distinct, however,
their field character, stratigraphy, and sedimentology are illustrated separately (Table 1 and below). Sandy-rock shorelines are those that have patches of rock exposed amongst sand and rocky outcrops thinly or partly covered with thin, discontinuous beach sand (Figure 4F).

These different types of shorelines are systematically distributed around the islands on these atolls (Figure 5). On Maiana, for example, rocky (-rubble and -bedded) shorelines are most common on the oceanward shoreline, whereas mangrove shorelines occur only on those shorelines facing the lagoon, and, even there, are abundant only in more protected areas, such as the re-entrants at the north and south end of the island. The distribution of mangroves near the north end of Aranuka is broadly comparable to those on Maiana, but mangroves are less common in the protected lagoon interior. Instead, the lagoonward flank of Aranuka includes broad stretches of rocky shoreline, unlike Maiana, and the southern margin which borders the reef apron is sandy and gravelly. The oceanward side of both Maiana and Aranuka islands includes a mix of sandy and rocky shorelines. Unlike Aranuka, Maiana includes long stretches of sandy-rock shoreline, especially in the southeast-facing margin.

In contrast, Tekaeang, on the west side of Aranuka atoll (Figure 1B), has a mostly sandy shoreline, with the exception of rocky area on the southwest margin and mangroves in the protected lee of a spit system on the northeast part of the island. Bikentekai, in the center of Aranuka atoll (Figure 1B), is completely surrounded by a sandy foreshore (although mangroves colonize much of the northern, protected shore), and some of the smaller islets on Maiana atoll include sandy shores on their ocean- or lagoon-facing margin and dense mangroves on the protected, island-facing flank.

**Foreshore Morphology and Sedimentology**

**Lagoonal sandy foreshores**

The morphology and sedimentology of sandy shorelines facing the lagoon are different from those on the oceanward side of the islands, so these are described separately. Sandy foreshores which face into the protected lagoon of Maiana atoll are flanked offshore by a broad (several 100 m) sandy intertidal flat. This intertidal flat includes oblique bars evident on remote sensing data, but these are generally indistinguishable in the field because of their very low amplitude (<15 cm). As described above, a comparable broad intertidal flat is absent on Aranuka, except in its northern extent, and wholly subtidal environments lie within 50 m of the shore in most areas. On both atolls, the ToB of lagoonal sandy foreshores is indicated by a sharp break in slope, frequently accompanied by a dark, coarse sand to gravel lag (Figure 6A). From the ToB, the sand to fine gravel foreshore forms a uniform surface dipping ~3-5 degrees and less than 2.5 m high, with most measured profiles <2 m high (Figure 6A,B).

Foreshore profiles are capped by vegetation or a small scarp, generally less than 0.5 m tall. The upper foreshore in many areas is bare sand marked by abundant crab burrows, made of poorly to moderately sorted, medium to coarse sand rich in mollusc, red algae, and foraminifera fragments (Figure 6C). These pass downdip into gently sloping middle shoreface sediments with sedimentologic characteristics generally similar to those of the upper shoreface, except that crab
burrows are less abundant (Figure 6D). The ToB sediments include very poorly sorted silt to gravel dark-colored lags rich in gastropod, bivalve, foraminifera, and scattered red algal fragments (Figure 6E). Offshore sediments of the burrowed intertidal flat include very poorly sorted silt and sand with numerous gastropod tracks and trails (Figure 6F).

Oceanward sandy foreshores

The sandy foreshores on the oceanward flanks of the islands are in many cases flanked by an irregular, but generally flat, rocky surface. This rocky reef platform forms the surface onto which the ToB downlaps. These foreshores can exceed 3 m height and dip oceanward at 5-9 degrees, higher and steeper than sandy lagoonal foreshores.

The berm on oceanward sandy foreshores varies laterally; some are densely vegetated, whereas others some areas include a small scarp (<60 cm). The upper foreshore commonly is a planar, dipping surface with medium to coarse sand, comprised of broken and abraded fragments of corals, foraminifera, mollusks, and red algae (Figure 7C). Crab burrows occur locally, but less commonly than in the upper foreshore of lagoonal settings. A thin layer of coral rubble commonly occurs near the high-tide level in the middle foreshore, but otherwise, sand-sized grains are akin to those in the upper foreshore. Towards the lower foreshore, grain size generally increases slightly, and sorting decreases. This transition down the shoreface is accompanied by an increase in the abundance of whole foraminifera and a concomitant decrease in the abundance of broken and abraded skeletal fragments (compare Figure 7C and 7D). Sediments of the lower foreshore include abundant whole to fragmented foraminifera, coral, and red algal grains which form a poorly to moderately sorted coarse sand to gravel (Figure 7E). In some areas, a thin (< 20 cm) rippled sand or coarse coral rubble can be found at the just offshore of the ToB (Figure 7F,G).

Exceptions to these general sedimentologic trends in oceanward shorelines occur at the northern and southern margins of the largest islands of Maiana and Aranuka atolls. In these areas, foreshore sediments are markedly coarser, comprised of a very poorly sorted coral, red algal, and foraminiferal sand to coarse gravel. In some places, these gravelly foreshores flank several successive ridges which bound a lower area, now filled with shallow pond(s); in other areas, a pronounced erosional scarp occurs just landward of the foreshore. As illustrated below, these island-ends with the coarse gravels are some of the most dynamic parts of these islands.

Mangroves

Mangrove shorelines occur on at least parts of most of the larger islands (Figure 4B). The mangroves of Maiana, Aranuka, and Tekaeang are found in more protected areas of lagoonal shorelines, and include dense stands. In some protected areas, the mangrove fringe is narrow (<10 m), and coconut palms occur proximal to bare sediment, with no obvious break in gradient.
Rocky Foreshores

Although not a focus of observation of this study, the rocky foreshore regions merit brief note because they do appear to play an important role in coastal morphology and shoreline dynamics (Richmond, 1993). As discussed briefly above, two end-member types of rocky shores (rubble and bedded) have a distinct outcrop and petrographic character.

The rocky-rubbly shores commonly form outcrops that extend outward, normal to the shoreline (Figure 4D). These outcrops are generally less than 2 m tall, massive, and unbedded. In some outcrops, however, two or more beds 30-100 cm thick may be evident; only rarely are crude laminations, fining-upward trends, or imbricated clasts present. Lithologically, these beds include two broad types: a) boundstone, including *Heliopora* in growth position (Figure 8A); and b) a coral-red algal-skeletal fragment rudstone with a packstone to grainstone matrix and abundant isopachous, fibrous cement (Figure 8B). In both types, skeletal fragments, including aragonitic components, are well-preserved. As these occur ~0.4-0.6 m above the level of living *Heliopora*, these type of deposits have been reasonably interpreted to represent deposition during the middle Holocene relative high in sea level (Schofield, 1977; McLean and Woodroffe, 1994; Richmond 1993).

The rocky-bedded foreshores are distinct in that they extend along the shoreline, and include well-defined bedding (Figure 8C,D,E). The shallowly dipping beds can form rocky cuestas on the shoreline, which can be discernable on the remote sensing data. These thin to thick bedded units can have sharp lateral contacts with (Figure 8C), and in some cases lie above, the rocky-rubble deposits (Figure 8D). These units range from well-sorted sands similar to nearby unconsolidated beach sands to skeletal rudstone (gravel-sized grains). Sedimentary structures include trough cross-lamination, coarse-fine laminations (Figure 8E), fining-upward laminations, and keystone vugs (Figure 8F). Diagenetically, these deposits include ubiquitous evidence for vadose diagenesis, including pendant (Figure 8G) and meniscus fibrous aragonite (?) cement. Collectively, these results suggest that these strata represent ancient beach deposits.

Nature of Shoreline Change

Shorelines are not static features, but instead change at several time scales. The Kiribati shorelines examined in this study are no exceptions; evidence for change can be found in the field and by comparison between different vintages of remotely sensed data.

Field evidence

Evidence for change in shoreline position can be found in the field on all islands (some of which are illustrated in the context of historical change below). Evidence for erosion includes exposed roots of terrestrial vegetation on the beach profile, trees stranded in the foreshore, and erosional scarps up to 1 m tall. To attempt to mitigate erosion in inhabited parts of the atolls, residents have taken several steps, including construction of groins, seawalls and simply piling vegetation and trash at the high-water line.
Although evidence for erosion can be found in many areas, some shorelines are accretionary. This shoreline state is suggested by linear, shore parallel ridges with vegetation that becomes successively smaller (e.g., younger) towards the present shore, groins with asymmetric sediment distribution and by houses built on stilts (e.g., originally over the water) now underlain by beach sediments.

Remote sensing evidence

The field observations of shorelines and areas of apparent change served as invaluable calibration points for interpretations of remote sensing data. These insights were utilized for mapping the nature and position of shorelines across the atolls and on historical remotely sensed imagery, which in turn illustrate how these shorelines have changed through time.

Several areas on these atolls are characterized by marked change. The most pronounced changes are found at the northern and southern end of the largest, north-south oriented islands of Maiana and Aranuka. Near the north end of Maiana, for example, the shoreline swings from trending east-west to trending north-south, broadly akin to a fish hook (Figure 9A). Between 1969 and 2009, parts of the northwest-facing shore eroded over 60 m (> -1.5 m/yr) (Figure 9B,C), in an area marked today by a pronounced scarp (Figure 9D), topped palms and a coarse dark gravel lag just offshore from the beach (Figure 9E). Most recently, between 2005-2009, the shore has stepped back up to 8 m (up to -2 m/yr) along this margin.

In contrast, just south of this area, the west-facing shore has accreted. A small, southward-directed spit present in 1969 on the west-facing shore filled and enclosed a small embayment by 2005 (Figure 9F,G). Similarly, between 2005 and 2009, a gravel spit on this shore has extended to the south over 100 m (>25 m/yr) (Figure 9G,H,I,J). Collectively, these observations suggest pronounced net sediment longshore transport to the south.

The southern end of Maiana also includes a fish-hook shape broadly analogous to that at the northern end of the island. On this margin, several changes have occurred, the most evident of which is filling of an inlet between two islands. In 1969, this area had a southwest-directed spit extending into an inlet (Figure 10A), but the inlet was completely closed between 2005 and 2009 (Figure 10B,C), the result of spit net migration of almost 200 m between 1969 and 2009 (5 m/yr). Beyond this lateral accretion, along this part of the island between just 2005 and 2009, the oceanward shoreline has prograded up to 14 m (~ +4 m/yr) in some areas, and eroded up to 6 m (~ -1.5 m/yr) in others.

The oceanward shorelines in areas other than the ends of islands have changed as well. In the southern end of Aranuka, for example, a series of barred beaches within embayments are separated by natural, rocky jetties. Each of these barred beaches have rotated counterclockwise between 2005 and 2009, with up to 8 m erosion in their northeastern extent, and up to 10 m accretion in their southwestern ends (Figure 11A,B). This general trend is present on open shorelines in the area as well, with up to 12 m of erosion just southwest of natural jetties, and up to 9 m accretion in areas alongshore to the southwest (Figure 11C). A broadly comparable pattern is present in northeastern Maiana (Figure 12). Here, between 1969-2009, an embayment in the shoreline has
accreted up to 48 m (+1.2 m/yr), whereas the more exposed area to the northwest has eroded up to 10 m (-0.25 m/yr). Most recently, between 2005-2009, this shoreline in the embayment has built oceanward up to 9 m (+2.3 m/yr), although the more exposed area shows no discernable change in this time period.

Some lagoonal shores have changed. The southern end of the lagoonal shoreline of Aranuka is flanked by a well-developed reef and reef apron (Figure 1B). In this area, rocky shoreline outcrops exposed near the atoll margin pass on-platform into a sandy gravel shoreline. Between 2005 and 2009, in the village of Baurua, a body of gravelly sand has migrated ~50 m (12.5 m/yr) northeastward alongshore (on-platform), resulting in a complex pattern of erosion and accretion in this area during this period (Figure 13A,B). A house that was offshore low lies over a gravel bar (Figure 13B, green circle and inset), although in another area (to the southwest along the shoreline, Figure 13B), a resident reporting marked erosion built a rock groin to stop erosion along his shore.

Numerous other lagoonal shorelines near the villages on both islands have changed during this time period. In these areas, many changes in the position of shorelines are associated with placement of groins, which disrupt longshore transport. In several villages where groins have been built, the groins have captured sediment on the upstream side. Downstream, however, even in a period of a few years, shorelines have de-stabilized and eroded, changing from straight to broadly wavy (Figure 13C,D,E). The irregular shoreline has peaks and recesses with periods of 25-75 m and amplitudes of <5 – 10 m. These disruptions tend to be the sites of erosion.

Many areas on Maiana that had well-established stands of mangroves in 1969 have expanded markedly, with the lagoon edge of the mangroves building lagoonward up to 83 m in 40 years (> +2 m/yr) (Figure 14). Additionally, in a gross sense, the length of mangrove shorelines on Maiana is expanding. More than 5% of the shoreline along the lagoonal shore that was sandy in 1969 had changed to mappable mangrove growth by 2009. Aranuka has less abundant mangrove shorelines, and no older aerial imagery, so conclusive evidence of the character of mangrove shorelines from there is lacking.

Smaller islets change as well. For example, between 1969 and 2009, a small islet on Maiana atoll (Figure 15A,B) was stable around much of its perimeter, with many areas changing (both accretion and erosion) less than 5-10 m. The southern tip of the islet closest to the lagoon eroded up to 90 m (-2.3 m/yr), however, and erosion is continuing, as suggested by the erosional scarp and trees in the foreshore (Figure 15C). The shoreline just to the north and west of this area has prograded, however, with up to 40 m accretion in this 40 year period, and mangrove growth on the southeast facing margin has been accompanied by island expansion as well.

Similarly, Bikentekai islet, on Aranuka atoll just east of Tekaeang, is a sandy islet. It is elongated with an east-west long axis that has been characterized by marked accretion on its western tip and erosion of more than 12 m on its eastern margin (Figure 14D,E,F). The south-facing flank is broadly accretionary, with numerous areas of young vegetation or unvegetated berms (Figure 15G), but includes local areas of minor erosion related to passage of nearshore bars. Sandy islets such as these appear to include some of the most dynamic shorelines on these atolls.
Island-scale change

The shoreline trends can be placed in an atoll-scale context. Maps of the direction (accretion vs. erosion) and magnitude of shoreline change (Figure 16) on these atolls reveals several trends (synthesized in Figure 17).

Since 1969, the lagoonal shorelines of Maiana are largely accretionary (Figure 16A,C, 17A). Some of this trend reflects the growth of mangrove shorelines (as discussed above), which expanded at a mean rate of 0.2 cm/yr during this interval. Some of this lagoonal accretion occurs on sandy shorelines, however, in some cases exceeds 10 m; the average rate of change on sandy lagoonal shorelines during this interval is mean accretion (+0.2 m/yr). In contrast, the oceanward margin of Maiana shows a more complex pattern during this time period (Figure 16A,C). Although there is considerable along-shore variability, the general patterns can be described to include four general areas (from north to south; Figure 17): a) the northeast-facing margin – mixed to accretionary, b) the east-facing margin that forms the convex-eastward bend in the island - erosional, c) the concave-eastward bend in the island – stable to slightly accretionary; and d) the southeast-facing southern third of the island – erosional. Considering the entire length of sandy ocean shorelines, the mean rate of change was just over 0.0 m/yr, net accretion.

Considering only the period between 2005 and 2009, however, the patterns on Maiana differ somewhat from the long-term trends (Figure 16B,D, 17). In this time interval, in contrast to the long-term trend of lagoonal accretion, lagoonal shorelines were mostly stable (no discernable change) to erosional; the mean rate of change of the sandy lagoonal shorelines during this period was erosion of -0.2 m/yr. Only locally are there small stretches with accretion, mostly associated with the larger villages (see discussion above; Figure 16B, 17). Oceanward shores illustrate contrasting patterns as well: a) a northeast-facing margin that is erosional in the longer-term is accretionary between 2005-2009; b) a convex-eastward bend in the island includes a mix of stable and erosional shorelines, broadly comparable to the longer-term trend; and c) the remaining southeast-facing margin is stable to accretionary, distinct from the long-term erosion especially notable in the southern part of the island. Collectively, however, sandy oceanward shorelines are characterized by accretion at a mean rate of +0.1 m/yr.

The spatial patterns of change for the 2005-2009 time period on Aranuka atoll illustrate some trends similar to, and others distinct from, those on Maiana (Figure 16E,F, 17). For example, although the northeast- and southeast-facing ocean shorelines of Aranuka island are largely accretionary, akin to Maiana, those that trend more north-south are more likely to be erosional. The average change on oceanward sandy shores reflects a net erosion rate of -0.2 m/yr, however, contrasting with the average accretion on Maiana. The lagoonal shoreline also includes patterns different from Maiana, with the erosion in the south and the stable to erosional shorelines further north. These general trends are reflected in the higher rate of change on the sandy shorelines here, with a mean rate of erosion of -0.5 m/yr. As on Maiana, however, the areas of erosion are concentrated around the villages (Figure 17C). The broad areas of stability on Aranuka lagoonal shores reflect the generally rocky foreshores, however, a class which is not common on the lagoonal shores of Maiana.
Islands other than the larger, windward islands change as well. Tekaeang island, on the west side of Aranuka atoll, includes a unique morphology (Figure 1B), and has different patterns of foreshore change (Figure 16C,F). The mean change on sandy shorelines of this island during this period is net erosion (mean is just under 0 m/yr). Here, much of the western third of the island includes a shoreline that has been erosional between 2005 and 2009, including shorelines facing south, west, and north. In contrast, the southeast-facing shoreline with the offshore sandy intertidal flat (Figure 1B, inset) includes a broad stretch of accretionary foreshore. The north-east facing shoreface includes complex patterns of accretion and erosion, related to migration of nearshore welded bars. A net accretion is suggested, however, by the presence of a southeast-prograding spit on this

Temporal changes

The characteristics of rates of change can be evaluated by an assessment of exceedance probability (log scale) versus rate of change (absolute value, on a linear scale) (Figure 18). Exceedance probability is \( P = \frac{m}{n+1} \), where \( m \) = ranking of rate of change from smallest to largest and \( n \) = number of samples. It represents the cumulative probability \( P[X \geq x] \) of a stretch of shoreline with rate of change \( X \) having a rate greater than \( x \). Stated another way, the data represent the probability (y-axis) that a given stretch of shoreline will have a rate of change equal to or greater than a given rate (x-axis).

A lower slope for a given group of data indicates that, for a certain probability (y-axis), the rate of shoreline change observed at random will probabilistically have a rate of change (x-axis) greater than that for a group of data which have a lower slope. For example, considering the entire island, there is a 1.1% probability (exceedance probability =0.01) that a given stretch of shoreline on Maiana between 1969 and 2009 had a rate of change of greater than or equal to \( \sim 1.0 \) m/yr; in contrast, on Maiana between 2005-2009, there is a 3.4% probability that a shoreline had a rate of change of greater than or equal to 1.0 m/yr. In other words, data with lower slopes are probabilistically characterized by shorelines with greater rates of change.

Collectively, these data illustrate that the rate-probability distributions for shorelines on Maiana and Aranuka atolls are roughly the same for the 2005 to 2009 time interval. In contrast, the longer-term data from comparison of Maiana shorelines from 1969 and 2009 have a distribution that contrasts with the other data sets. Much of the shoreline is characterized by relatively low rates of change (areas with rates of <0.2 m/yr). Such shorelines make up 49% of the Maiana 1969-2009 data, 58% of the Maiana 2005-2009 data, and 49% of the Aranuka 2005-2009 data). From this point, however, the trends in the data are divergent, with the shorter term data illustrating that shorelines are characterized by greater rates of change from 2005 to 2009.

This trend of greater rates of change more recently is evident in data from comparison of data from both the sandy oceanward (Figure 18B) and lagoonward (Figure 18C) shorelines.
**Interpretation**

The most recent (December 2009) observations from the South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) suggest that the trend in sea level at Tarawa is a relative rise of +4.3 mm/yr. Extrapolating this rate suggests that sea level changed ~16 mm during the study interval (3.667 yrs between collection of the 2005 and 2009 images). This relatively small change alone is likely insufficient to drive the observed changes, or, as stated by Woodroffe (2008), “erosion of an individual shoreline is far more likely to result from local or proximal causes ... than to be attributable to ... [relative] sea‐level rise” (p. 90).

Oceanographic and atmospheric shifts associated with ENSO variability are another possible driving mechanism. In Kiribati, La Nina conditions, such as those which dominated between 2005 and 2009, are accompanied by “normal” tradewinds from the east and sea level lower than during El Nino phases. Under these conditions, it might have been expected that leeward (western) island shores would be stable or even accretionary, but erosion might be more common on the eastern, windward margins. Several observed patterns are generally consistent with those predictions. Specifically, stronger winds (and larger waves) from the east may explain:

- the erosion (central islands) and longshore transport and accretion (north and south ends) of the eastern flanks of the main islands of Maiana and Aranuka;
- the erosion on the eastern margin of Bikentekai islet, and accretion on its western side;
- the accretion of the south-east facing flank of Tekaeang may be related to long- and onshore movement of sediment from the adjacent broad sand flat.

The widespread observations of erosion on the leeward (lagoonal) shores of the largest islands may appear broadly inconsistent with this general conceptual model. With dominant winds from the east, it might be expected that west-facing shores would be protected, and stable or accretionary. This apparent paradox may be related to the influence of settlements on these lagoonal shores, however. As illustrated above, shores in these villages commonly are modified by groins or other structures that stop or slow the “normal” longshore transport, which will cause local erosion. On Maiana and Aranuka, many other lagoonal shores are indeed stable.

The observation that rates of change are elevated during the past four years is intriguing. This dynamic could be explained by two end-member possibilities. On one hand, this trend may be real, and reflect decreased shoreline stability as a response to an increased rate of rise in sea level, due to larger waves or stronger currents, or some other natural dynamic. Alternatively, the trend may simply reflect capture of higher-frequency shoreline variations, changes that may reverse or change rates through time around some mean (e.g., the "dynamic equilibrium" of Woodroffe).

Clearly, a predictive understanding of shoreline dynamics of Kiribati awaits additional studies.
Potential Implications

The focus of this status update is to provide data on the character of shoreline change on atolls in Kiribati. These results could several possible implications of general relevance:

1. Shorelines change; they are unstable by nature. Under any conditions, it is unreasonable to suggest that they will not change.
2. Attempting to stop the change may lead to further unintended consequences. An example in these data is illustrated by the erosional “hot spots” in the lagoon of Maiana that are associated with the villages, and construction of groins. In stopping the longshore movement of sand to protect one area, the downstream shoreline is starved of sediment and will erode.
3. It is an overstatement to suggest that the islands are disappearing by erosion. Some areas are indeed eroding – as discussed above, evidence for erosion is common around villages, which is important because people live there, but is also not representative of the islands as a whole. In many areas, the shoreline is actually building out.
4. Nonetheless, many areas are eroding, and at rates that are alarming. The rate of change appears to be increasing.
5. The observation of the most pronounced changes occurring near the ends of the islands may have implications for other atolls. For example, on Tarawa, the most populous atoll in Kiribati, a substantial number of the residents live on Betio and Bairiki, near the end of the chain of islands. Even in the absence of any human impacts, this area might be expected to see marked change. It is possible that the marked changes there (e.g., documented in many SOPAC reports through the years; e.g., Carter 1983; Forbes and Hosoi, 1995), although perhaps modified by human impacts, and not necessarily caused by the population.
References Cited


# Appendix 1. General Workflow

<table>
<thead>
<tr>
<th>Preliminary Analysis of Remote Sensing Data</th>
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<tbody>
<tr>
<td>Identify stable areas, areas of change, range of shoreline types</td>
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<tr>
<th>Field &amp; Lab Observations</th>
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<tbody>
<tr>
<td>Collect DGPS data</td>
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<tr>
<td>Characterize sediments and geomorphology</td>
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<tr>
<td>Calibrate and validate remote sensing interpretations</td>
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<table>
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<th>Change Detection</th>
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<tr>
<td>Geo-rectify images</td>
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<tr>
<td>Manually digitize shorelines for available data</td>
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<td>Compare shoreline location and type</td>
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<table>
<thead>
<tr>
<th>Analysis</th>
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</thead>
<tbody>
<tr>
<td>Plot spatial patterns</td>
</tr>
<tr>
<td>Illustrate statistical patterns</td>
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Appendix 2. Georectification

The multi-temporal satellite imagery and aerial photos provided a valuable data set for assessment of the nature and scale of change through time. In this study, images were georectified using ERMapper, with the general strategy as follows.

The first step was to correct the positional error on the most recent satellite images (2009), by adjusting each to the mapped DGPS data. Because these data were from numerous locations around the islands, the positions were well constrained. This step was fairly straightforward, accomplished by moving the registration point, which essentially shifted the entire images several meters.

The second step was to adjust the older (2005) images, assuming the 2009 data to be geopositionally correct. This was done the same manner as the initial georectification. Errors were qualitatively visibly evaluated by comparison of known points between images, and revealed only minor errors, much less than the changes mapped between the images.

Because they had no a priori spatial information, and there existed the possibility of warping or distortion, aerial photo georectification was more challenging. Using the aerial photos provided by the Ministry, a number of ground control points (GCPs) were identified on each image; these points are locations that can be confidently identified on both the aerial photo and the remote sensing image. In most cases, this process was straightforward, but on a few images with no villages or rocky outcrops, identifying suitable points was a major challenge. To provide the best-constrained correction for shoreline change analysis, GCPs were focused on and around the islands, avoiding unnecessary skewing. For each image, an absolute minimum of 6 GCPs were identified, and these were used for second-order transformation. During transformation, the GCP coordinates and the corresponding real-world locations are used to calculate a least-squared function, which is then used to assign real-world coordinates to the entire aerial photo. The GCP points are not "locked," but are fitted using the calculated function, and thus after transformation, the GCPs on the aerial photo and the base layer (the 2009 image) will have slightly different coordinates. These differences provide a means to assess the possible errors. This step is accomplished by measuring the root mean square error (RMSE),

\[ RMSE = \left[ (x_s - x_r)^2 + (y_s - y_r)^2 \right]^{0.5} \]

Where \(x_s\) and \(y_s\) are the coordinates in the original source aerial photo, and \(x_r\) and \(y_r\) are the coordinates in the rectified aerial photo. Summary statistics for RMSE calculations are summarized in Table A2-1.

These steps create aerial photos with pixels of various sizes, and so final step of georectification re-samples the entire image to equalize pixel size. All of the aerial photos were resampled using cubic convolution, with pixels of 0.5 m, comparable to the WorldView base data.

Because this study used aerial photos with different numbers and quality of GCPs, as the detailed interpretations proceeded, each aerial photo was continually evaluated for possible errors, especially where aerial photos overlapped. If errors or differences were found in areas with overlap, the more accurate aerial was utilized. Although a systematic study of errors was not
undertaken, the results indicate evident errors are consistently less than a few meters, much less than the magnitude of change in many areas between 1969 and 2009.

Because even a low rate of change (e.g., >0.2 m/yr, the smallest bin in Figure 18) means a measured difference in shoreline position of >8 m (0.2 m/yr = 8 m/40 yr), it greatly exceeds the RMSE (Table A2-1) (this interpretation is broadly consistent with that of Webb (2006), who used aerial photos and lower-resolution (4 m² IKONOS) data). Thus, although there is undoubtedly some mapping error, it is less than the geopositional error for these data. These areas of marked change are those of most interest to this study, and of relevance to the island residents.

Areas with "small" changes nonetheless likely include a greater percentage of error. To attempt to mitigate for this, the results (e.g., Table 2) report mean values of change calculated from several thousand data points, which (assuming no systematic bias) effectively removed the small errors.

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**Average** 3.0
Figure 1. A) Location of Kiribati in the equatorial Pacific. B) Remote sensing image of Aranuka atoll. On this atoll, the main island is oriented roughly north-south, and lies on the eastern, windward margin of the atoll. Unlike most atolls in Kiribati, there is a large island in the western flank, Tekaeang, that includes a complex series of beach ridges (inset). The sandy islet of Bikentekai is highlighted by the orange arrow. C) Remote sensing image of Maiana atoll. Note the large island on the eastern windward flank, with hooks at the end of the islands. Along much of its lagoonal extent, the island is rimmed by a broad sandy intertidal flat, a feature not evident on Aranuka.
Figure 2. Plots of climatic variables, including wind direction and magnitude for La Nina (A) and El Nino (B) (from Richmond, 1993) phases from Tarawa (capital of Kiribati) and Multivariate ENSO Index (C) [modified from http://www.cdc.noaa.gov/enso/enso.current.html]. Note that marked La Nina phases (blue, departure < 0) occur roughly every 10 years (previously centered on ~1989, ~1999-2000, and 2008), and there is a 2010 transition from La Nina to neutral or El Nino conditions.
Figure 2B. Photos of field assistants. A) Daniel Doolittle and assistants; B) Tion Uriam; C) Puta Tofinga; D) Kabure Yeeting; E) Mayor Taiki, Aranuka; F) Our guide, Maiana; G) The Masked Marauder.
Figure 3. Representative topographic profiles across the islands. (upper) Maiana and (lower) Aranuka. Note the broadly similar features (oceanward and lagoonward beach ridges, central depression), even though they have markedly different widths. See text for discussion.
Figure 5. Summary maps of the distribution of different shoreline classes for the three largest islands, Maiana and Aranuka atolls. See text for discussion.
Figure 6. Caption on next page.
Figure 6. Characteristics of lagoonal sandy shorelines, from a representative shore, Tebanga, central Maiana. A) Field photo of lagoonal sandy foreshore. Note the darker grains near the toe of beach, near where people are walking; these are readily visible on remote sensing data. B) Representative DGPS profile across the beach in this area, datumed (0) on the toe of the beach. Note the relatively low beach height, less than 1 m. C-F) Paired field and thin section (grain mount) photographs of upper foreshore (C), middle foreshore (D), lower foreshore (E) and offshore (F) regions. Scale bar on all photomicrographs is 500 µm. See text for discussion.
Figure 7. Caption on next page.
Figure 7. Characteristics of oceanward sandy shorelines, from a representative shore, Nuotaea, northern Maiana. A) Field photo of oceanward sandy foreshore. Note the marked contrast between the rocky reef platform (to the left, “rp”) and the bright beach. These contrasts make the contact between the two readily visible on remote sensing data. B) Representative DGPS profile across the beach in this area, datumed on the toe of the beach. Note the beach height of up to 3 m, greater than the lagoon. C-E) Paired field and thin section (grain mount) photographs of upper foreshore (C), middle foreshore (D), lower foreshore (E). The offshore (F) region includes either a thin (< 20 cm thick) accumulation of rippled sands (F) or a rocky surface (G), part of the reef platform. Scale bar on all photomicrographs is 500 µm. See text for discussion.
Figure 8. Caption on next page.
**Figure 8.** Characteristics of rocky shorelines.  
A) Rocky-rubble shoreface, of *in situ* *Heliopora*, now above sea level. Features such as this have been interpreted to reflect a higher position of sea level in the past.  
B) Thin section photomicrograph from a rocky-rubble shoreface. Note the diverse fauna, and the isopachous cements which rim the pores (open pores are filled with blue epoxy). Northeast Tekaeang island, Aranuka.  
C) Contact between rocky-rubble (R-r) and rocky-bedded (R-b) rock types, illustrating a sharp lateral transition. Atintabuariki, Aranuka.  
D) Outcrop photo panorama of area illustrating relations between rocky-rubble (R-r) and rocky-bedded (R-b) types. In this area, *in situ* *Heliopora* (part A; near backpack) pass upward into a fining-upward, coral-debris-rich succession (yellow arrow). This succession (R-r) is sharply (dashed yellow line) overlain by bedded coarse coral-red algal-skeletal rudstone to grainstone dipping seaward at 5-10 degrees. This upper unit is distinctly finer than that below, and no *in situ* corals, although it includes coral gravel. Nuotaea area, north Maiana.  
E) Outcrop photo of rocky-bedded rock type. Note the coarse-fine layering and the coarse coral rubble. Other outcrops include sediments that are very similar to the extant, loose shoreline sand. Tebwangatua area, Maiana.  
F) Thin-section photomicrograph of fenestrae (labeled “f”), or multigranular roofed pores, common in beachrock. Baurua area, south Aranuka.  
G) Thin-section photomicrograph of pendant, or dripstone, cement. This cement morphology is consistent with precipitation in the vadose zone, above the water table. Baurua area, south Aranuka. Scale bar on all photomicrographs is 500 μm.
Figure 9. Caption on next page.
**Figure 9.** Remote sensing images and field photos of changes at the north end of Maiana. A) Overview of part of the “fish hook” at the northwest end of the island. The position of the 1969 shoreline (dotted orange line) is overlain on the 2009 remote sensing image, and illustrates net erosion in the north, accretion in the south. The yellow boxes are the locations of the remaining images. B and C) Paired 1969 (B) and 2009 (C) image of the northern area with marked erosion. This erosion is evident from the 1969 shoreline (dashed orange) to the 2005 shoreline (dashed red), to today (the background image). D) Field photo, illustrating the gravelly substrate exposed in a beach scarp from this area. E) Field photo of toppled trees and dark lag, from the area with the greatest erosion, directly onshore from the red arrow on C. F – H) Paired 1969 (F), 2005 (G) and 2009 (H) images of the accretionary and progradational shoreline (the larger, southern yellow box in A). I) Field photo of the broad, gravelly shoreline with a paucity of vegetation, consistent with its youth. J) Field photo of the coarse gravel. Lens cap for scale.
Figure 10. Paired 1969 (A), 2005 (B) and 2009 (C) images of part of the south Maiana shoreline. During this time period, what was in 1969 a partly open an inlet between two islands has closed, the result of longshore progradation from northeast to southwest. Other parts of the shoreline (highlighted by the red arrows) have eroded through this time period, however.
Figure 11. Paired 2005 (A) and 2009 (B) remote sensing images of part of the southeastern Aranuka oceanward shoreline. In this area, several beaches within embayments have rotated counterclockwise, with erosion to the northeast and progradation to the southwest. C) Image of larger area of the southeastern Aranuka shoreline, with the magnitude of change (in m) from 2005-2009 superimposed. Warmer colors represent erosion, cooler colors reflect accretion.
Figure 12. Remote sensing images of part of the northeast-facing Maiana shoreline. In the area, from 1969 (A) to 2005 (B) to 2009 (C), part of this shoreline has prograded markedly. In contrast, the area to the northwest has eroded somewhat. D) Low-angle aerial photograph of this area, illustrating the influence of the rocky natural groins. The white arrow points to the same rocky outcrop noted in part C.
Figure 13. A-B) Paired images from 2005 (A) and 2009 (B) from the village of Baurua, southern Aranuka lagoonal shoreline. In this area, gravelly sand has been transported to the northeast, or lagoonward, along the shore in this time period. On (B), the dashed red line represents the position of the 2005 shoreline. The green circle highlights a house, now over the sandy gravel bar (inset), that was over water in 2005, and the yellow arrow points to the end of a groin that was recently constructed. C-D) Paired images from 2005 (C) and 2009 (D) from a lagoonal sandy shoreline, Tebanga, central Maiana. In 2008, a seawall was built, which has resulted in a change in shoreline from generally straight (in C) to more irregular (highlighted by the arrows in D). E) Field photo along the shoreline, illustrating its irregular, undulatory appearance. This irregularity is manifest as highly variable along-shore patterns of erosion and accretion.
Figure 14. Paired images from 1969 (A) and 2009 (B), from a lagoonal area in central Maiana. In this area, as with much of the lagoonal shoreline of Maiana, the mangroves have expanded considerably during this period.
Figure 15. Remote sensing images and field photos of character of changes on representative smaller islets. A) Aerial photo (1969) of a small islet, northeast Maiana. B) Remote sensing image (2009) of the same area, indicating the position of the 1969 shoreline and the magnitude and direction of change (colored dots). C) Field photo of eroding palm trees from the southeastern part of this islet. D) Remote sensing image (2005) from Bikentekai islet, Aranuka atoll. E) Remote sensing image (2009) from same area, with the position of the 2005 shoreline and the magnitude of change noted (colored dots). Note the erosion on the eastern (windward) margin and the general accretion on the western (leeward) margin. F) Field photo from the eastern margin of the island, with a scarp more than 1 m tall exposing root mats and soils. G) Field photo (looking southeast) from the western part of the islet, illustrating the young vegetation in this area, consistent with its progradational nature.
Figure 16. Caption on next page.
Figure 18. Plots of rate of change for shorelines versus the exceedance probability.  A) All shorelines, by atoll and time period; B) Sandy ocean shores only, by atoll and time period; C) Sandy lagoon shorelines only, by atoll and time period; D) Maiana atoll only, by lagoon versus oceanward shore. See text for discussion.
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<th>Shore Type</th>
<th>Characteristics</th>
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<td>Rocky - rubble</td>
<td>Rocky outcrops of coarse, coral-rich debris</td>
<td>Most abundant on ocean shorelines (M,A)</td>
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<td></td>
<td>Poorly sorted conglomerates up to pebble size</td>
<td>Locally occurs on lagoon shorelines (A)</td>
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<tr>
<td></td>
<td>Isopachous fibrous cement</td>
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<tr>
<td></td>
<td>Generally unbedded, massive; rare faint imbrication</td>
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<tr>
<td></td>
<td>Shore-normal elongation, form shoreline promontories</td>
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<tr>
<td></td>
<td>Most &lt; 50 m wide alongshore</td>
<td></td>
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<tr>
<td>Rocky - beachrock</td>
<td>Rocky outcrops of sandy to coarse, skeletal-rich debris</td>
<td>Most abundant on ocean shorelines (M,A)</td>
</tr>
<tr>
<td></td>
<td>Grains include corals, foraminifera, red algae, molluscs</td>
<td>Locally occurs on lagoon shorelines (A)</td>
</tr>
<tr>
<td></td>
<td>Coarse-fine laminations, keystone vugs, pendant cement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seaward-dipping beds common</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shore-parallel elongation</td>
<td></td>
</tr>
<tr>
<td>Sandy - rock</td>
<td>Gradational between Rocky – beachrock and Sandy</td>
<td>Both ocean or lagoon shorelines</td>
</tr>
<tr>
<td></td>
<td>Intimate mix of thin sand cover, small rocky outcrops</td>
<td></td>
</tr>
<tr>
<td>Sandy</td>
<td>Seaward-dipping beachface</td>
<td>Both ocean and lagoon shorelines, but sedimentologically and morphologically distinct</td>
</tr>
<tr>
<td></td>
<td>Height, dips, sediments highly variable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sediments from medium sand to gravel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ocean-side heights up to 4 m, lagoon-side heights &lt; 2 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foraminifera rich (ocean) to skeletal rich (lagoon)</td>
<td></td>
</tr>
<tr>
<td>Mangrove</td>
<td>Shoreline with a mappable dense mangrove stand</td>
<td>Lagoon shorelines only</td>
</tr>
<tr>
<td></td>
<td>At least a few mangroves wide; locally exceeds 50 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>In some areas, bound landward by a relict beach</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Table summarizing the nature, character, and distribution of different types of shorelines, Aranuka and Maiana atolls.
Table 2. Data on magnitude and rates of change.