Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll

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ABSTRACT

The geological stability and existence of low-lying atoll nations is threatened by sea-level rise and climate change. Funafuti Atoll, in the tropical Pacific Ocean, has experienced some of the highest rates of sea-level rise (~5.1 ± 0.7 mm/yr), totaling ~0.30 ± 0.04 m over the past 60 yr. We analyzed six time slices of shoreline position over the past 118 yr at 29 islands of Funafuti Atoll to determine their physical response to recent sea-level rise. Despite the magnitude of this rise, no islands have been lost, the majority have enlarged, and there has been a 7.3% increase in net island area over the past century (A.D. 1897–2013). There is no evidence of heightened erosion over the past half-century as sea-level rise accelerated. Reef islands in Funafuti continually adjust their size, shape, and position in response to variations in boundary conditions, including storms, sediment supply, as well as sea level. Results suggest a more optimistic prognosis for the habitability of atoll nations and demonstrate the importance of resolving recent rates and styles of island change to inform adaptation strategies.

INTRODUCTION

Low-lying coral reef islands are coherent accumulations of sand and gravel deposited on coral reef surfaces that provide the only habitable land in atoll nations such as Kiribati, Tuvalu, and the Marshall Islands in the Pacific Ocean, and the Maldives in the Indian Ocean. These islands are sensitive to changes in physical boundary conditions (sea level and wave regime) at a range of temporal scales from short-term extreme events (Maragos et al., 1973; Kench et al., 2006) to seasonal (Kench and Brander, 2006) and decadal variations in climate-ocean processes (Flood, 1986; Webb and Kench, 2010), though they have had a few thousand years to achieve equilibrium size, shape, and position on reef surfaces (Kench et al., 2005). The combination of their low elevation, small areal extent, sensitivity to variations in boundary conditions, and high population densities has raised global concern about the future stability and existence of mid-ocean atoll nations (Barnett and Adger, 2003; Nicholls and Cazenave, 2010). From a geological perspective, rising sea level is expected to erode island coastlines in a Bruun-type (Bruun, 1962) response, forcing remobilization of sediment reservoirs and promoting island destabilization. In extreme cases, wholesale erosion and/or destruction of islands is projected, making them unable to support human habitation and rendering their populations among the first environmental refugees (Khan et al., 2002; Dickinson, 2009). Despite such bleak assertions, few studies have considered the mode and magnitude of physical changes in islands that will affect the security of atoll nations over the next century. This gap in understanding island geological adjustments to sea-level rise is a major barrier to supporting adaptation and risk reduction strategies in atoll nations (Barnett and O'Neill, 2012).

While future rates of sea-level rise and island geomorphic response can be debated, rates of sea-level rise and island stability over the past century are less equivocal and offer insights into the modes and magnitude of island adjustment to sea-level rise.

Tide gauge observations show a global mean sea level (GMSL) rise during the 20th century of ~1.7 mm/yr (Church et al., 2013), while satellite altimetry data indicate faster rates, between 2.8 and 3.6 mm/yr, since 1993 (Church et al., 2013). Data also show that sea-level change is not spatially uniform, with the western tropical Pacific Ocean, the location of several atoll nations, experiencing rates of sea-level rise three to four times faster than the GMSL between 1993 and 2010 (Becker et al., 2012). In marked contrast to the extensive research effort to define sea-level behavior over the past century, no study has attempted to determine how atoll islands have responded to the sea-level signal over a comparable centennial time frame.

Here we present a centennial-scale record of physical changes in the islands of Funafuti Atoll, Tuvalu (8°S, 179°E; Fig. 1), in the central Pacific Ocean. Funafuti provides the unique opportunity to resolve questions concerning island response to rising sea level due to the existence two temporally significant data sets. First, a rare 118-yr-old baseline survey exists from Funafuti Atoll that allows subsequent changes in island shorelines to be documented. Second, the atoll is located in a region that has experienced sea-level rise of ~5.1 mm/yr over the past 60 yr (Fig. 1A), corresponding to a total increase in sea level of ~0.30 ± 0.04 m (Becker et al., 2012), and a rate approximately three times larger than the GMSL from 1950 to 2009.

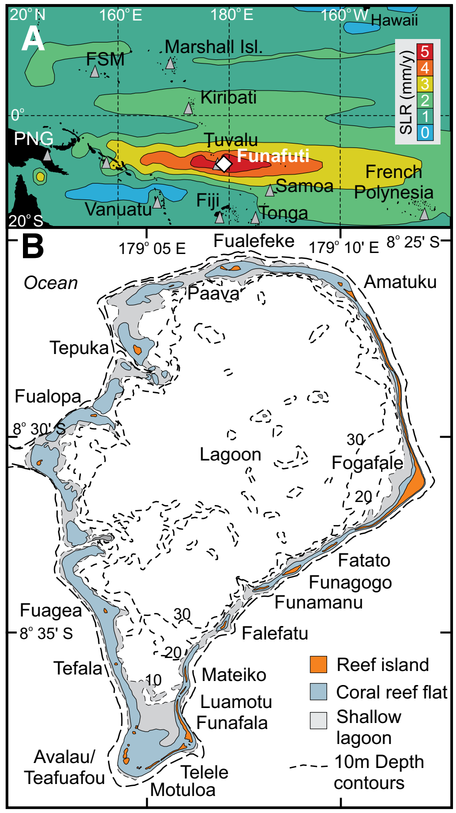

Figure 1. Funafuti atoll, Tuvalu, central Pacific Ocean. A: Rates of sea-level change (sea level rise, SLR) in central Pacific, A.D. 1950–2009, after Becker et al. (2012). Locations of Funafuti Atoll and south Pacific tide gauge network are also shown. FSM—Federated States of Micronesia; PNG—Papua New Guinea. B: Funafuti Atoll showing study islands.

Consequently, Funafuti is an ideal laboratory to examine the morphological responses of islands to recent sea-level rise.

FIELD SETTING AND METHOD

Funafuti Atoll is ~25 km north-south and 17.5 km in width and contains 32 islands on the atoll rim (Fig. 1B; Fig. DR1 in the GSA Data Repository[1]). The islands vary in size, sedimentary composition, and level of human modification. This study examines the planform changes

[1]GSA Data Repository item 2015184, methods, Tables DR1 and DR2, and Figures DR1–DR4, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, June 2015; v. 43; no. 6; p. 515–518; Data Repository item 2015184 | doi:10.1130/G36555.1 | Published online 27 April 2015

on 29 islands (eight sand, nine gravel, and 12 mixed sand and gravel islands) on the atoll rim (McLean and Hosking, 1991). Two of the study islands are inhabited (Amatuku and Fogafale). The data set is derived from multiple sources that include detailed geological maps of the islands on Funafuti surveyed during the Royal Society of London Expeditions in 1896–1898 (David and Sweet, 1904), aerial photographs (1943, 1971, and 1984), and satellite imagery (2005 and 2013) (see Appendix DR1 in the Data Repository for detailed methodology). In each temporal layer, the seaward edge of vegetation was determined as the island shore (Fig. DR2) following Webb and Kench (2010). Data from imagery was georectified and overlayed at a consistent scale to determine changes in planform properties of islands (Table DR2 in the Data Repository). Summary analysis concentrated on two time frames: aggregate changes over the entire 118 yr record; and differences in island change between 1897 and 1971 and between 1971 and 2013, the latter corresponding with the period of recently documented accelerated increase in the rate of sea-level rise.

TABLE 1. SUMMARY OF ISLAND AREAL CHANGES FROM A.D. 1897 to 2013 AT FUNAFUTI ATOLL, TUVALU

Island name	Change, 1897–2013		Change, 1897–1971		Change, 1971–2013	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
1. Fualefeke-Paava	2.55	48.8	3.07	58.5	–0.51	–6.2
3. Mulitefala	–0.29	–10.6	–0.47	–17.3	0.18	8.1
4. Amatuku	2.80	96.3	2.69	92.6	0.11	1.9
5. Fogafale	3.98	2.6	–0.60	–0.4	4.58	3.0
6. Fatato	–0.24	–4.3	–1.2	–21.4	0.96	21.7
7. Funagogo	–1.56	–12.4	–3.60	–28.5	2.03	22.6
8. Funamanu	–0.29	–6.9	–1.08	–26.0	0.79	25.8
9. Falefatu	0.37	11.6	–0.31	–9.6	0.68	23.5
10. Mateiko	1.32	47.5	1.08	38.7	0.24	6.3
11. Luamotu	0.43	35.2	0.43	35.0	0.01	0.1
12. Funafala	6.22	38.1	5.68	34.8	0.54	2.5
13. Tefota	–0.04	–21.7	–0.01	–3.6	–0.03	–18.8
14. Telele-Motusanapa	1.83	25.9	1.28	18.1	0.56	6.7
16. Motuloa	0.59	17.0	0.36	10.5	0.22	5.9
17. Nukusavalivali	–0.30	–38.4	–0.34	–44.4	0.05	10.8
18. Motugie	0.09	121.5	0.12	160.6	–0.03	–15.0
19. Avalau-Teafuafou	5.13	73.7	4.06	58.4	1.07	9.7
21. Tegasu	0.11	20.5	0.07	13.5	0.04	6.1
22. Tutaga	–0.09	–5.7	–0.05	–2.9	–0.05	–2.9
23. Falaoigo	0.42	44.5	0.21	21.9	0.21	18.6
24. Tefala	–0.86	–57.7	–0.71	–47.5	–0.15	–19.4
25. Fuagea	–2.53	–74.0	–1.78	–52.3	–0.74	–45.5
26. Fuafatu	2.04	153.3	1.69	126.6	0.36	11.8
27. Fualopa	–0.59	–21.3	–0.33	–12.0	–0.26	–10.6
28. Tepuka	–2.97	–23.2	–2.08	–16.2	–0.89	–8.4
29. Teafualiku	0.24	342.9	0.15	214.3	0.09	40.9

Note: Islands 2, 15, and 20 are skipped because on three occasions islands merged to form single islands.

CENTENNIAL-SCALE CHANGES IN ISLAND AREA

Aggregated data across the past 118 yr show three striking features of island areal change over the past century (Table 1; Table DR2; Fig. DR3). First, there has been no loss of islands from the atoll rim. Notably, even the smallest islands, with an area <0.5 ha, are still present. Second, total net land area of the study islands has increased by 18.50 ha (7.3%) since 1897. Third, there are marked differences in the magnitude and direction of areal change between islands. Over the past 118 yr, 18 of 29 islands had a net increase in area, totaling 33 ha, with a range from 3% to 343% growth. Excluding the smallest island (Teafualiku), each of the remaining 17 islands had an average increase of 1.88 ha (52.6%). The largest absolute increases in island area occurred on three of the larger islands: Funafala (6.22 ha, 38.1%), Avalau-Teafuafou (5.13 ha, 73.7%), and Fogafale (3.98 ha, 2.6%). The remaining 11 islands (38% of total) showed decreases in area ranging from –4.3% on Fatato (–0.24 ha) to –74.0% on Fuagea (–2.53 ha). Mean reduction in island area in this subset was –0.89 ha (~25.2%). The largest absolute reductions in island area of –2.97 ha and –2.53 ha occurred on Tepuka (–23.2%) and Fuagea (–74.0%), respectively.

MULTIDECADAL CHANGES IN ISLANDS

At the sub-centennial time scale, aggregated atoll-wide net island area increased by 8.3 ha (3.3%) between 1897 and 1971 (Table 1). Of note, over this 74 yr window, 16 islands (55%) were responsible for this increase (expanding a total of 21 ha with a mean increase of 1.61 ha). The largest absolute increases occurred on Funafala (5.68 ha), Avalau-Teafuafou (4.06 ha), and Fualefeke-Paava (3.07 ha). In this time frame, 13 islands (45%) showed a reduction in area (mean of –0.97 ha, 21.7%), most notably on Tepuka (–2.08 ha, 16.2%), Fuagea (–1.78 ha, 52.3%), and the three gravel islets on the eastern rim (Fatato, Funagogo, and Funamanu), which reduced in area by –1.2, –3.6, and –1.1 ha, respectively.

Over the 42 yr between 1971 and 2013, aggregated net island area increased by a further 10.1 ha (3.8%), or at a rate of 0.92% per decade compared with 0.45% per decade between 1897 and 1971. Of further significance is the fact that some islands changed from erosional to accretional trends (Fig. DR3). Over the period 1971–2013, 21 islands (72.4%) exhibited a net increase in island area. Islands with the greatest increase occurred along the atoll's eastern rim which includes Fogafale (4.58 ha, 3%), Fatato (0.96 ha, 22%), Funagogo (2.03 ha, 23%), Funamanu (0.79 ha, 26%), and Falefatu (0.68 ha, 24%), all of which experienced net erosion between 1897 and 1971 (Table 1; Fig. DR3). Only eight islands decreased in area over the 42 yr between 1971 and 2013. The largest decreases occurred on the sandy islands of Tepuka (–0.89 ha, 8.4%), Fuagea (–0.74, 46%), and Fualefeke-Paava (–0.51 ha, 6%). This latter island is the only one that shifted to an erosional trajectory between 1971 and 2013.

MODES OF PLANFORM ADJUSTMENT

Our results show that all islands experienced net changes in area. Such changes, mediated through differential shoreline erosion and accretion, are manifest in a range of styles of planform change that have previously only been inferred (Kench and Cowell, 2001; Fig. 2; Fig. DR4) or identified at shorter time scales (Webb and Kench, 2010).

Comparison of the area of the original island core of each island with the footprint of all island positions over the time frame of analysis (similar to the envelope of beach change, and termed the island change ratio, ICR) provides critical insights into the dynamism of islands (Fig. 3). For the majority of islands, a large proportion of the island core (>75%) persisted intact to 2013. Progressive reductions in island core relative to island footprint signify increasing change in either the position or areal extent of islands. Where such reduction conforms to a geometrical decrease or increase in island area, such islands either contract or expand on their reef surface (Fig. 3). Examples include Fuagea (western reef) and Paava (northern reef), which have respectively contracted and expanded on the reef rim (Fig. 2A). Between these geometric limits, islands display a higher degree of positional mobility whether they are increasing or decreasing in areal extent (Fig. 3).

Five major types of island adjustment have been identified. First, some islands have accreted or eroded around their entire perimeter, occu-

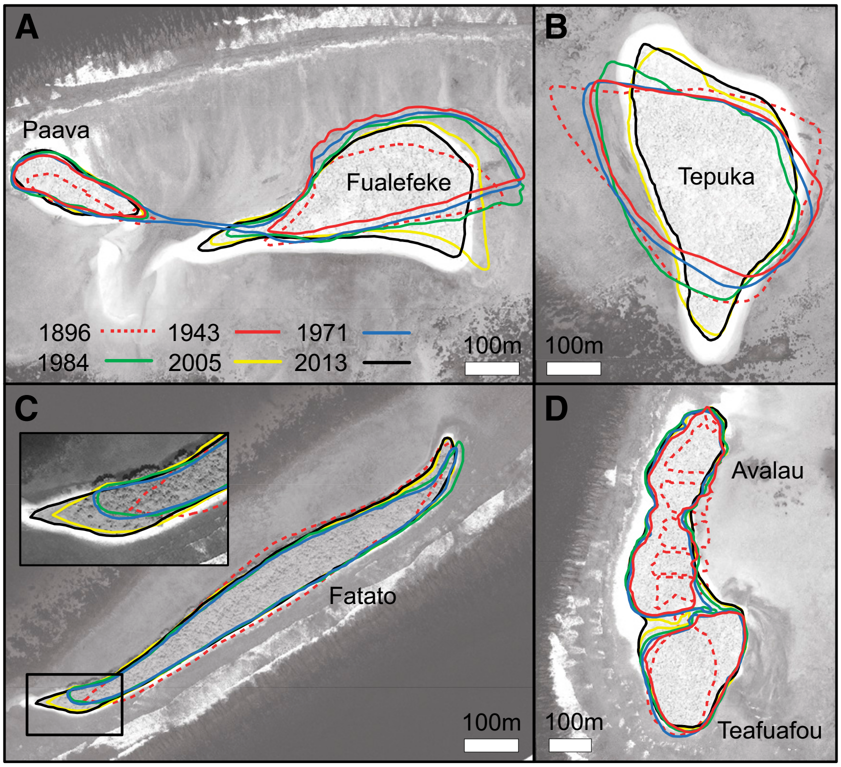

Figure 2. Changes in planform characteristics of selected reef islands in Funafuti Atoll (Tuvalu), A.D. 1896–2013, showing different styles of island adjustment. A: Expansion of Paava and rotation of Fualefeke. B: Rotation of Tepuka. C: Lateral extension of Fatato. D: Merging of Avalau and Teafuafou. Planform changes on all study islands are shown in Figure DR4 (see footnote 1). Location of islands is shown in Figure 1.

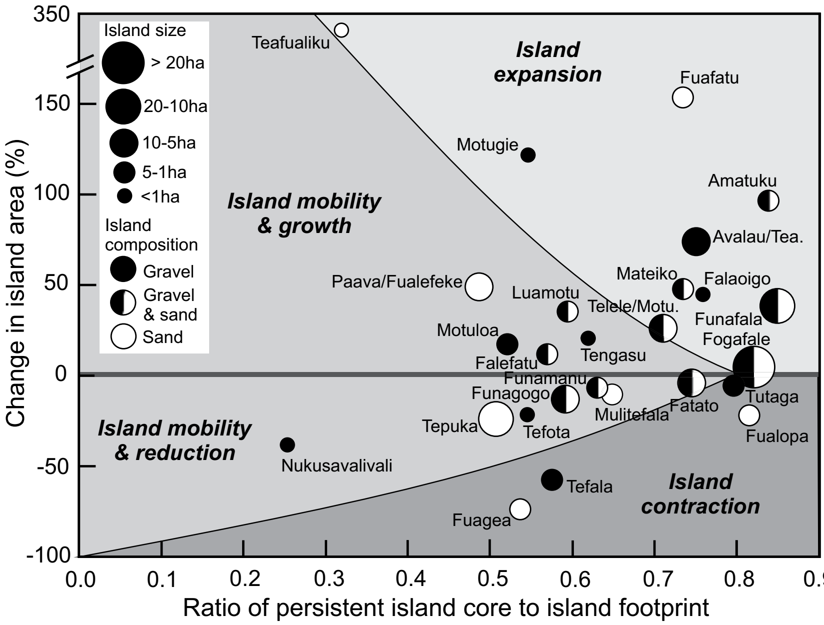

Figure 3. Dynamic adjustment of islands in Funafuti Atoll, Tuvalu, A.D. 1897–2013. Island change ratio depicts stable proportion of vegetated core against entire island footprint over time scale of analysis. Different styles of island adjustment are shown. Motu.—Motusanapa; Tea.— Teafuafou.

pying a larger footprint on the reef surface or contracting around their island core (expansion or contraction mode). Second, migration of islands has occurred through differential erosion of ocean and lagoon shorelines, with maximum migration of up to 50 m (e.g., Figs. 2A and 2B). In most cases, lagoonward migration has occurred (Figs. 2A and 2B); however, on the leeward (western) side of the atoll, a number of islands have migrated toward the ocean reef edge. Third, lateral extension of gravel spits has occurred on islands on the eastern margin of the atoll, governed by longshore transport of sediments supplied during storm events (Maragos et al., 1973; Baines and McLean, 1976). Maximum extension of 60 m is observed on Fatato (Fig. 2C). Fourth, in at least three instances neighboring islands have merged (e.g., Fig. 2D). Such island welding has occurred through alongshore sediment fluxes filling the shallow passages between islands. Once passages are blocked, lagoonward-directed sediments are trapped, leading to embayment infilling. Fifth, there is evidence of island rotation on several sand islands (Figs. 2A and 2B). In the case of the triangular-shaped Tepuka, rotation is manifest through clockwise movement of the northern and southern ends of the island and erosion of the lagoonward coastal margin. Such island rotation is a likely response to shifts in the process regime including storms.

MECHANISMS OF ISLAND CHANGE

Our results unequivocally show that the physical island response to increased sea-level rise over the past century, and particularly over the past 60 yr, has not been one of widespread erosion. Rather, the evidence demonstrates that the majority of islands increased in area during this time despite accelerated sea-level rise, and island change is sensitive to other local and shorter-temporal-scale processes such as changes in sediment supply, storm events, and human modification that may mask the influence of sea-level rise alone (Maragos et al., 1973; Baines and McLean, 1976; McLean and Hosking, 1991).

Only two of the study islands have permanent habitation. Amatuku increased in area by 96.3% over the past century; however, this is likely driven by significant modification of the shoreline. In contrast, on the largest settled island of Fogafale, there has been minimal direct shoreline modification (Yamano et al., 2007). Observed increases in area of Fogafale (2.6%) occur outside the main settlement and are believed to be forced by natural process, consistent with other islands on the eastern rim.

Interpretation of the ICR provides insights into the mechanisms of island change. As noted earlier, for the majority of islands, a large proportion (>75%) of the original island footprint persisted intact to 2013. On most islands, where there has also been a large increase in area and large positional adjustments, these changes have occurred through reworking of island margins and, more significantly, by the addition of fresh sediment to the island reservoir. In particular, on the eastern atoll rim, some elongate gravel islands (e.g., Funafala and Luamotu) have retained more than 90% of their original core, yet have increased in area by up to 40%. Such island accretion has occurred through generation of new gravel deposits during cyclonic events, which have subsequently been transported onto the island shoreline and alongshore to contribute to island extension as documented by Maragos et al. (1973) and Baines and McLean (1976). The generation of a large volume of cyclone-generated rubble is also responsible for the reversal of the erosional trend on other eastern rim islands. Between 1897 and 1971, Fatato, Funagogo, and Funamanu experienced substantial erosion of between 21% and 29%. However, post-1971, the islands have all accreted by a similar amount, with the net centennial record indicating minor change.

On islands that have decreased in area, less of the original island core has remained (Fig. 3). Island migration or rotation in such cases (e.g., Tepuka) has occurred where the sediment reservoir is in net deficit, no new net sediment input is occurring, and adjustments rely on greater reworking of the original core. Of note, a number of islands in this category (toward the left and bottom of Fig. 3) are sand islands located on the west and north rim of Funafuti. Such findings reflect the importance of sediment generation in the stability, growth, and persistence of reef islands, as highlighted by Perry et al. (2011), and may indicate a difference in the sensitivity of islands to dynamic change. In particular, gravel islands may possess a more stable resistant core around which further accumulation may occur, assuming episodic pulses of sediment are generated. In contrast, sand islands may be more susceptible to dynamic change and migration that involves reworking of island core sediments. Such islands require a continuous supply of sand-size material to sustain their size.

CONCLUSIONS

The value of using high-resolution data sets to resolve the magnitude and mode of recent landform adjustment to sea-level rise is demonstrated, which is valuable for informing landform trajectories in response to global climate change. Our results provide a cautiously optimistic future for small island nations. In a region where sea level has risen more than 0.30 m over the past century, and with rates of sea-level rise of 5.1 mm/yr over the past 60 yr, we do not detect widespread erosion or a large loss in island area. While a number of islands have decreased in size, the aggregated land area of islands of Funafuti Atoll has increased by 7.3% over the past century. Our data show that reef islands, which provide the only habitable land in atoll nations, are both robust and dynamic landforms that continually alter their size, shape, and orientation to a range of drivers that include sediment supply, storms, local coastal processes, human modification, as well as sea-level change. Furthermore, as demonstrated here from 29 islands, both the style and rate of change is highly variable. Significantly, our results show that islands can persist on reefs under rates of sea-level rise on the order of 5 mm/yr. However, sea level is projected to increase by 1.2 m by 2100, at rates double that of recent times, and it is unclear whether islands will continue to maintain their dynamic adjustment at these higher rates of change. The challenge for low-lying atoll nations is to develop flexible adaptation strategies that recognize the likely persistence of islands over the next century, recognize the different modes of island change, and accommodate the ongoing dynamism of island margins.

ACKNOWLEDGMENTS

We acknowledge SPC Geoscience, Fiji, for cooperation in facilitating the research.

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Manuscript received 22 December 2014
Revised manuscript received 24 March 2015
Manuscript accepted 26 March 2015

Printed in USA

Geology

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Geology 2015;43;515-518
doi: 10.1130/G36555.1

Notes