Advanced Review

Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise?

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The future of low-lying reef islands has been the subject of international concern, scientific debate, and media interest in the last decade. As a result of sea-level rise, atoll islands are expected to become increasingly unstable and to be susceptible to potential depopulation by the end of the 21st century. Some have suggested that sea-level rise has already resulted in widespread erosion and inundation of atoll islands. Here, we analyze the physical changes in over 200 islands on 12 atolls in the central and western Pacific in the past few decades when sea level in the region increased at rates three to four times the global average. Results show little evidence of heightened erosion or reduction in island size. Instead island shores have adjusted their position and morphology in response to human impacts such as seawall construction and to variations in climate–ocean processes. These changes are reviewed and the role of sea-level rise is evaluated. The implications of this analysis are addressed in two parts. First, we consider the proposition that future sea-level rise will destabilize atoll islands to such an extent that their inhabitants will be forced to migrate offshore. And second, we identify a series of new challenges relating to risk reduction and adaptation policy for atoll island governments, international agencies, and island communities. These require a substantial shift away from the present adaptation paradigm of external migration and focus on the persistence of atoll islands and in-country solutions.

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INTRODUCTION

Small island nations are at the front line of the impacts of climatic change and sea-level rise.[1,2] Most vulnerable are the atoll island nations, such as the Maldives in the Indian Ocean[3,4] and Kiribati, Marshall Islands, Tuvalu and Tokelau in the Pacific.[5,6] In these nations, the only habitable land for settlement, agriculture, and infrastructure are small low-lying reef islands, whose surfaces rarely reach an elevation greater than 2–3 m above mean sea level. The sediments that make up the islands comprise unconsolidated biogenic sand and coral rubble sourced from the adjacent reef and lagoon and deposited by waves and currents on the rims of atolls or on interior reefs in their lagoons. Not only are the islands among the youngest landforms on earth with radiometric ages of island deposits commonly in the range of 2000–5000 years BP,[7,8] but many islands are still developing physically where space is available on reef tops.[9] Island margins, beaches, and reef flats are also dynamic features being continually subject to changes in local and external environmental processes. The latter operate at a range of timescales from short-run episodic events such as storms and tsunami, through seasonal shifts in wave and wind direction and intensity to interannual and longer-term climate and ocean oscillations, notably associated with ENSO (El Nino-Southern Oscillation) cycles in the Pacific.[10,11]

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This combination of low elevation, unconsolidated sediments, small areal extent, sensitivity to variations in atmosphere–ocean boundary conditions as well as their limited soil and freshwater resources, economic capacity, and high population densities has raised global concern about the future viability—indeed the very existence—of these mid-ocean atoll nations. In fact, several authors have argued that as a result of sea-level rise, atoll islands will become physically unstable and unable to support human populations over the next century.[2,5,12] The most anticipated physical impacts of sea-level rise are shoreline erosion, inundation and sea flooding of island margins, seawater intrusion into fresh groundwater lenses and reduced resilience of island ecosystems including coral reefs, mangrove forests, and seagrass beds.[13] It has also been suggested that these impacts are already evident and that there has been widespread erosion and inundation in response to recent global sea-level rise.[5,14] Despite these claims, few studies have analyzed how islands have physically changed in response to the rising level of sea in the last few decades. Lack of such knowledge constrains development and implementation of appropriate risk reduction and adaptation strategies in atoll states. To date such strategies often have been based on false perceptions about the role of past and potential sea-level interactions with island shorelines rather than with realistic evidence-based impacts.

While the future pace of sea-level increase and island stability can be debated, rates of sea-level rise and island response over the past several decades are less equivocal. Thus far, the discourse has been one-sided and emphatic, highlighting an ongoing and accelerating crisis dominated by the spectre of sea-level rise, sinking islands[15] and disappearing[16] and Titanic states.[17] Lacking has been any objective examination of past and recent shoreline changes on atoll islands that have been subject to known increases in sea level. Such an examination is needed (1) to define the modes and magnitude of island shoreline response; (2) to see if it is possible to detect and attribute a clear sea-level rise signal in recent coastal changes on atoll islands; and (3) to distinguish such a signal from other coastal change processes, including those associated with human activity. Several recent studies suggest such an analysis can now be done.[18–26]

Here we review evidence on the nature and magnitude of shoreline change on atoll islands in the Pacific over the last few decades during which time the sea has risen globally at an average rate of 1–2 mm/year. In the central and western Pacific, where the atolls reviewed here are located, rates of sea-level rise have been in excess of the global average. We then explore the assumption that sea-level rise has resulted in widespread inundation and island erosion based on recent and emerging quantitative data on shoreline changes from over 200 islands on 12 atolls in the Pacific. Causes of the historical shoreline changes and trends are reviewed and the role of sea-level rise in explaining the changes evaluated. Finally, the implications of this analysis are addressed in two parts. First, we consider the proposition that future sea-level rise will destabilize atoll islands to such an extent that their inhabitants will be forced to migrate. And second, we identify a series of challenges relating to risk reduction and adaptation policy for atoll island governments, international agencies, aid donors, and island communities.

THE RISING LEVEL OF THE SEA AND ITS EXPECTED IMPACT

In the last decade, a great deal of research effort has been expended in reconstructing past and recent sea-level behaviour and trends. Over the past 130 years, there has been an unambiguous increase in averaged global mean sea level (GMSL) of approximately 200 mm, with 20th century rates of 1.5–2.0 mm/year based on tide gauge records and faster rates from 1993 to 2009 of ~3.3 mm/year since the availability of satellite altimetry.[27,28] Rates of sea-level rise are however not uniform across the globe and large regional differences have been detected. In the tropical western and central Pacific rates up to three to four times faster than the global average have been reported between 1993 and 2009[29,30] (see Figure 1).

Superimposed on these trends of rising sea level in the Pacific are the transient interannual variations in sea surface elevation that reach heights of up to 40 cm above and below average levels[31] and are clearly shown in the Pohnpei and Funafuti records since the mid-1970s (see Figure 1(c)). These large oscillations are linked to natural climate phenomena such as ENSO (El Niño-Southern Oscillation) cycles, while shorter-term high (and low) sea levels associated with predictable 'king' tidal cycles, unpredictable storm surges, and distant-source swell waves can result in saline inundation and flooding.[32,33]

In marked contrast to the extensive research effort to define sea-level behaviour over the past century, there have been few attempts to determine how atoll islands have responded to the rising level of the sea over the same time frame. This is surprising since the fragility of reef islands and the potential impact of sea-level rise was recognised by the Intergovernmental Panel on Climate Change (IPCC)

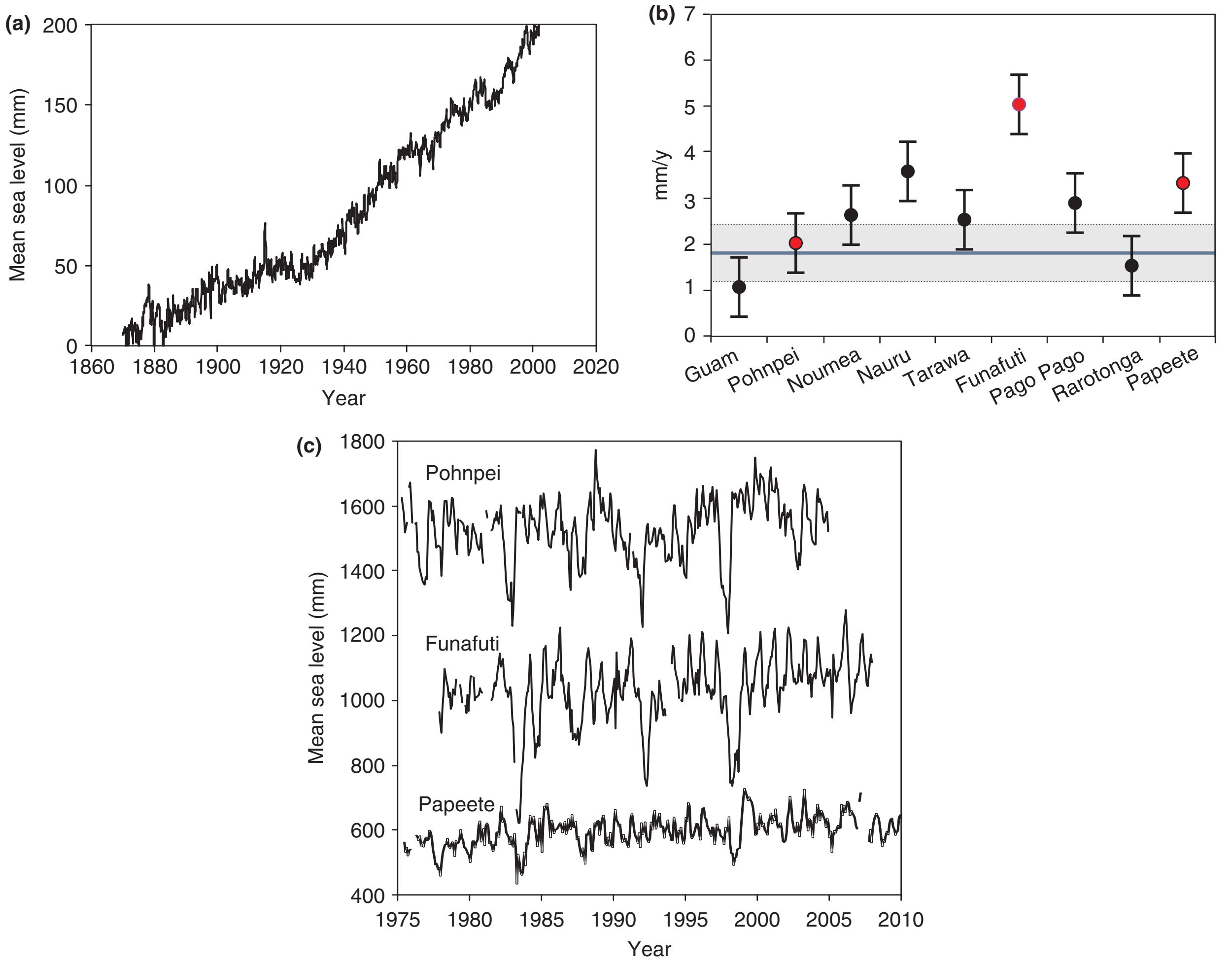

FIGURE 1 | Global and Pacific sea levels. (a) Global mean sea-level rise (GMSL) in mm from 1870 to 2009. (Reprinted with permission from Refs 27 and 28. Copyright 2011 Wiley Blackwell; Springer). (b) Total sea-level rise in mm/year at stations across the Pacific from west to east estimated over the period 1950–2009 based on annual reconstructed sea level (RESL) and continuous global positioning system (GPS) records of vertical land motion. The horizontal line represents the global mean sea-level trend over this period of 1.8 mm/year with error band of ±0.5 mm/year. (Reprinted with permission from Ref 30. Copyright 2012 Elsevier Ltd.). (c) Sea-level records from the 1970s for three tide gauge stations Pohnpei, Funafuti, and Papeete in the western and central Pacific. The sites are close to the atolls where studies of multidecadal island shoreline changes have been undertaken (see Figure 3 for locations). (Source: Monthly data from Permanent Service for Mean Sea Level; http://www.pol.ac.uk/pmsl/)

in its early assessments,[34,35] and in recent years there has been substantial media and academic attention to the plight of atoll islanders especially around the issue of resettlement and migration as a consequence of sea-level rise.[2,14–16] But, despite assertions of island fragility and vulnerability, few studies have quantified island morphological change at the same temporal scale (decadal) as the detailed sea-level record.

Notwithstanding the limited evidence documenting the instability of island shorelines, sea-level rise has been implicated as the primary mechanism to promote shore erosion, destabilize coastal systems, and ultimately destroy islands.[5,12,16] Rarely however is specific evidence of shore erosion provided, or the reasons why erosion should take place, described. Scarping of island beaches, exposure of intertidal beachrock outcrops, undercutting of strand vegetation, and especially toppling of coconut palms have been cited as evidence of severe erosion ascribed to relative sea-level rise ever since Darwin first used such observations in the Cocos (Keeling) Islands in 1836 to support his subsidence theory of coral reefs.[36] We now know that localized shoreline erosion on Cocos,[37] as on other atolls, can be quite ephemeral and can result from several natural factors including episodic storms from which the shore later recovers, or from erosion-accretion cycles associated with the seasonal shift of winds and seas during monsoonal conditions.[10,37]

Equally rarely is the mechanism equating island erosion with sea-level rise described, though the Bruun Rule is most commonly implicated either explicitly or implicitly.[38] In fact, the Bruun Rule is advocated in the UNFCCC's handbook on methods to evaluate impacts and adaptation to climate change as an appropriate tool to 'estimate the response of the shore profile to sea-level rise' though the handbook does caution that the model is only 'applicable for small-scale local sites'.[39] The Bruun model envisages that the nearshore profile will be eroded and move landwards and upwards as a function of the magnitude of sea-level rise (roughly a 1-cm rise in sea level erodes beaches about 1 m horizontally), but its applicability in reef island situations, that have shore profiles very different from continental beaches, has been seriously questioned.[40] Elsewhere, there have been calls to 'abandon' the Bruun Rule[41] though it is still used to project future erosion of sandy beaches at the global scale.[42] An alternative model based on observations of reef change after a coral bleaching event in the Seychelles suggests that an increase in sea level will raise water depths across reef surfaces and allow higher wave energy to impact ocean-side shorelines, the end result being island erosion not dissimilar to that of the Bruun effect.[43]

Two more complex models have been specifically developed for atoll island situations though neither the shoreline translation model (STM)[40] nor the sediment allocation model (SAM)[44] has been widely adopted for island vulnerability studies. The STM includes not just sea-level rise but also island width, elevation, and changes in sediment supply, while the SAM assumes islands develop by hybrid accretion (both lateral and vertical accretion) toward an equilibrium constrained by limited accommodation space. The application of these models to real-world atoll situations is limited to a few sites, but they do mark a significant improvement in our capability to identify the relative roles of sediment availability and sea-level rise to forecast future changes in island conditions.[9]

Collectively, these shoreline-change models do suffer from the fact that they are essentially two-dimensional, whereas atoll islands are very much three-dimensional entities. Unlike continental beaches and coasts, atoll islands have a continuous perimeter extending 360°, which means they can be impacted by marine and atmospheric processes from all directions. Atolls also have windward and leeward sides and the islands ocean- and lagoon-facing shorelines. Not only do these geographical differences result in contrasting process and energy regimes but they are also reflected in differences in reef forms, island topography, and sediment caliber around the perimeter and across the interior of an atoll.[9,13] For instance, in central Pacific atolls four types of island have been recognised based on morphology, sediment and rock characteristics, and position on the atoll with each island type conforming to a typical 'equilibrium condition' that can be used to infer an island's behaviour over century-long timescales[45] (see Figure 2).

Such differences in island form, sediment characteristics, and process regimes have hindered the development of an appropriate general model that adequately describes the relationship between sea-level rise and reef island response, though this has not stopped speculation about the potential impact of sea-level rise or the development of adaptation policies.

SEA-LEVEL RISE IMPACTS ON ATOLL ISLANDS: LOOKING BACK TO LOOK AHEAD

In the absence of any robust planform models of reef island change, historical analogues have been used to ascertain how atoll islands have faired during past periods of sea-level rise. Geological analogues illustrating the formation and growth of atoll islands in parallel with rising sea levels during the mid-Holocene have been described from atolls in the Maldives[46] and the Marshall Islands[47] though such analogues are not of universal applicability and the temporal (millennial) scale of island development is vastly different to the decadal scale of recent sea-level rise and that projected through to 2100.

However, because we are currently in a time of ongoing global sea-level rise—and have been for the past several decades—there are now good opportunities to assess the impacts of such conditions on atoll islands. We also have some of the basic resources such as vertical aerial photographs extending back to mid-last century and more recent satellite imagery as well as appropriate tools and techniques to undertake sequential analyses of images. The former provide snapshots of islands' past; the latter allows quantification of how atoll shorelines have behaved in the interim. Recent studies differ from earlier attempts to assess island changes based on historical maps, charts and photographs, anecdotal evidence, questionnaires, and field surveys.[48] Such investigations suffered from patchy and incomplete geographical and temporal coverage and difficulties in aligning diverse datasets to a common scale and spatial template. While the results from such analyses provide useful information on the magnitude and nature of island and shore changes—a good example being that of changes on

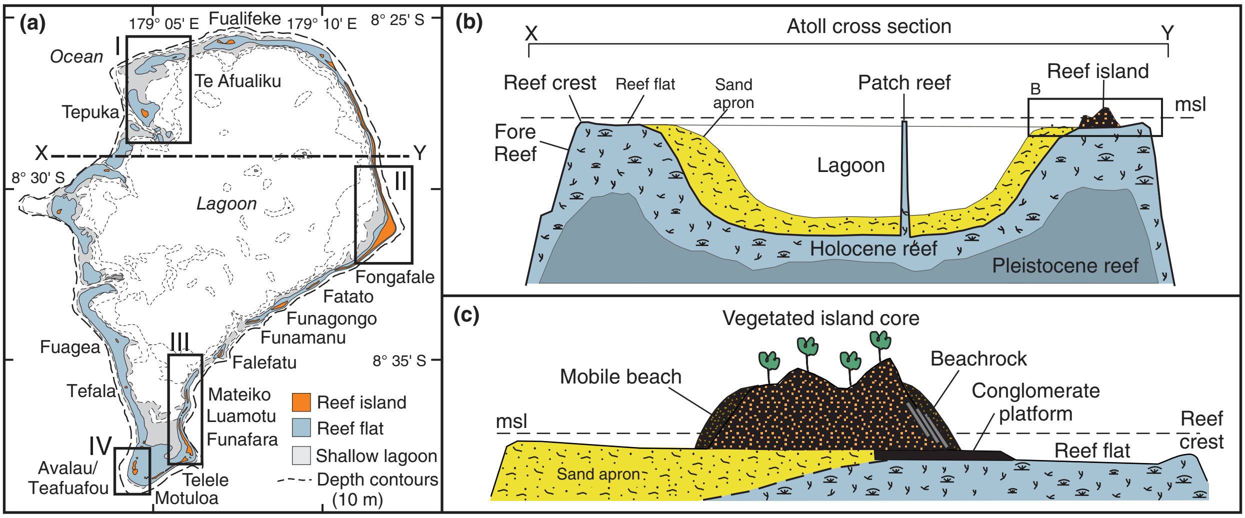

FIGURE 2 | Atoll and reef island morphology and structure. (a) Funafuti atoll in the central Pacific with its reef perimeter and lagoon. The atoll is approximately 25 km N–S and 18 km E–W. There are 33 islands on the reef rim, the boxes showing locations of the four types of atoll islands found in the central Pacific: Type 1 islands are composed of sand, roughly symmetrical to oval in shape, typically located on leeward atoll rims near reef passages (Box I). Type 2 islands are developed at convex-seawards bends of atoll rim (Box II), commonly boomerang or horseshoe shaped with coral gravel ridges to seaward and sand ridges along lagoon shores. Type 3 islands are narrow and elongate, occur on straight narrow reefs (Box III), and comprise sediments and topography similar to Type 2 islands. Type 4 islands are complex structures of mixed coral gravel and sand, developed on cemented rubble, rectangular in shape, separated by narrow passages (Box IV). (Source from Ref 45). (b) Cross-section of a typical atoll showing major structural elements including deep lagoon (20–50 m) and reef rim with islands, reef flat, and reef crest identified. (c) Atoll island commonly 50–100 m wide with a high ridge on the ocean side (right) and lower ridge on the lagoon side (left) showing vegetated core and mobile beaches along both shores and cemented beach sand (beachrock) and cemented coral rubble (conglomerate). ((b) and (c) Reprinted with permission from Ref 9. Copyright 2009 Cambridge University Press).

Palmyra atoll since 1874[49]—they do not provide an adequate framework for more quantitative analyses, especially of planform and island area changes.

Methodological protocols relating to historical shoreline changes are now well established[50,51] and an emerging literature, using comparable tools and analytical techniques, has enabled more rational comparative studies from several locations across the Pacific (see Figure 3).

Table 1 summarizes the study sites that cover over 200 islands on 12 atolls. Methodologies are fully described in each of the cited references.[19–26] Typically shoreline-change studies use the line of the 'toe of beach' (ToB) or 'outer edge of strand vegetation' as a proxy for the island shore as the high or low water marks are harder to recognize and vary virtually on a daily basis. Usually the island planform is manually digitized from a sequence of geo-rectified images using ArcGIS, the results commonly being analyzed through a digital shoreline analysis system (DSAS) to generate statistics of shoreline change, patterns of shoreline movements, and changes in beach and island area.[50,52] Of critical importance is the use of a consistent geo-referenced coordinate system for overlaying sequential layers of data. With the digitized shorelines, two different measures of island change are normally derived: surface area and shoreline position and the changes between time periods.

MULTIDECADAL STUDIES OF ATOLL ISLAND CHANGE

Of the studies listed in Table 1, five provide data on whole-island area changes; the others focus on beach changes in the central parts of islands away from the most active island termini,[26] or are concerned with the differences in shore response between the lagoon and ocean shores.[20,24] The investigations of whole-island area and planform changes cover 146 islands, the results of which are summarized in the accompanying figure (see Figure 4).

In Figure 4, data have been normalized to 'decadal change' because of the different time periods between the first and last time-slice at each of the sites (see Table 1). Over two thirds (106) of the 146 islands fall within a ±3.0% envelope of change in island area, an error range largely determined by image resolution and measurement of shoreline position.[19] Such islands can be regarded as being in a steady state[45] or stable[23] condition. In most instances, the change in island size

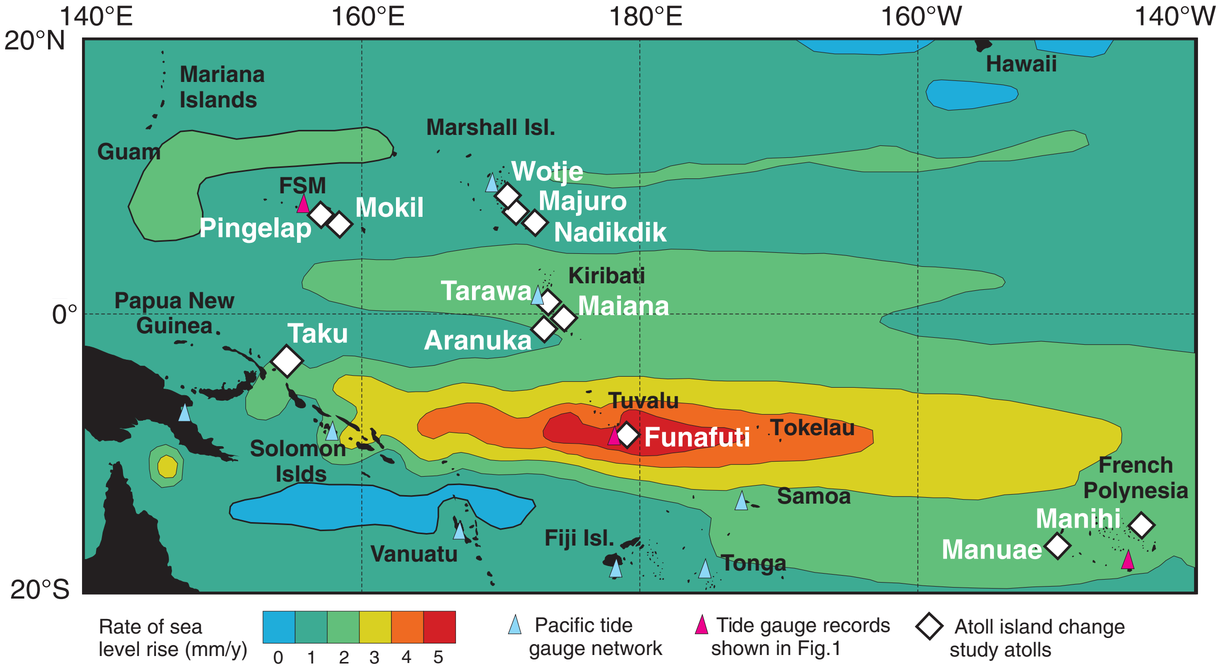

FIGURE 3 | Map of the central and western Pacific showing reconstructed mean sea-level trends in mm/year between 1950 and 2009. (Reprinted with permission from Ref 30. Copyright 2012 Elsevier Ltd.). Includes location of tide gauge stations for sites identified in Figure 1(b) and (c) and the location of atolls where the studies of multidecadal island shoreline changes reviewed here have been undertaken.

TABLE 1 | Multidecadal Changes in Atoll Islands in the Central and Western Pacific Ocean

Location/Country	Atoll	Latitude: Longitude	Number of Islands	Time Period	Reference
Tuvalu	Funafuti	8.30S:179.07E	17	1984–2003	19
Kiribati	Tarawa	1.25N:172.79E	4	1955–2004	19
FSM	Pingelap	6.13N:160.42E	3	1944–2006	19
FSM	Mokil	6.40N:159.45E	3	1944–2006	19
Kiribati	Maiana	0.56N:172.59E	17	1969–2009	20
	Aranuka	0.10N:173.36E		2005–2009	
Marshall Is	Majuro	7.06N:171.11E	15	1967–2006	21
Marshal Is	Wotje	9.26N:170.03E	52	1945–2010	22
Kiribati	North Tarawa	1.30N:172.02E	41	1968–1998	23
French Polynesia	Manuae	16.32S:154.40W	6	1955–2008	24
	Manihi	14.24S:145.57W	41	1961–2001	24
Marshall Is	Nadikdik	5.54N:172.09E	29	1945–2010	25
PNG	Taku	4.45S:157.00E	16	1943–2012	26
Total	12		244		

was less than ±0.5 ha with 50 islands changing by less than ±0.1 ha. Of the remaining 40 islands (28%) that are outside of the ±3.0% envelope, 28 indicate island expansion while the other 12 islands decreased in size. Note that all of the latter are concentrated in the group of the smallest islands <1 ha in area (see bottom left of Figure 4). On the other hand, accretion occurred across all island sizes and none of the islands larger than 1 ha recorded a reduction in area. These results also show the preponderance of accretion over erosion in the sample islands. But they do justice neither to the variations and differences between islands nor to the nature of, and reasons for, the changes that are detailed below.

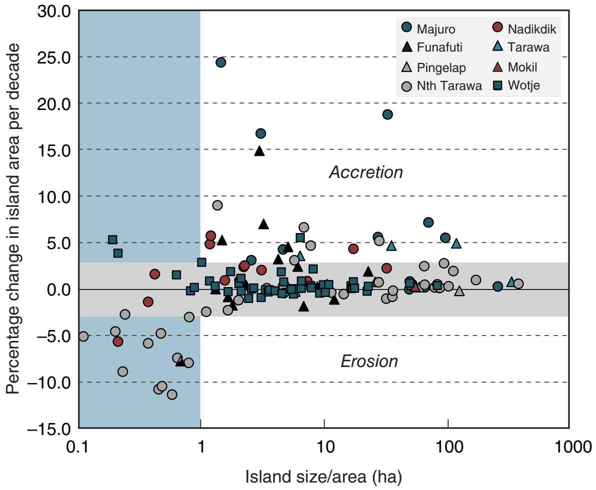

FIGURE 4 | Summary data of island area and percentage decadal change at seven atoll sites. Island-change data within the highlighted ±3.0% band width is not considered significant and following Ref 19 islands in that group are regarded as being stable. (Data sources from tables as follows: Funafuti, Tarawa, Pingelap, Mokil ,Table 2, Ref 19; Majuro, Table 2, Ref 21; Nadikdik, Table 1, Ref 25; North Tarawa, Table 5, Ref 23; Wotje, Table 3, Ref 22).

Growing Islands with Rising Seas

The first quantitative study of physical changes on atoll islands was published in 2010.[19] It examined 27 islands on four atolls in three central Pacific states (Federated States of Micronesia, Kiribati, Tuvalu) over a 19–61-year period (see Figure 3 and Table 1). During this time, 20 of the 27 islands either maintained the same size or increased in area either through lagoon shore accretion or the lateral extension of elongate islands. The remaining islands exhibited a net reduction in area primarily as a result of erosion of ocean-facing windward shorelines. One notable feature of the results was that net changes in island area and shoreline position from the first to last time frame were smaller than gross changes between successive shorter surveys, indicating the shores of atoll islands are dynamic changeable landforms. This dynamism is evident in the later studies.[20–26] Also, foreshadowed was the major contrast between: (1) those atoll islands that have been largely affected by human activity notably the urban islands where any sea-level rise signal is expected to be quite weak; and (2) those rural or outer islands where natural processes continue to dominate and where the sea-level rise signal should be less blurred than on the urban islands.

Capital Atolls: Contrasting Shoreline Changes Between Urban and Rural Islands

Follow-up studies of Majuro and Tarawa, the capital and most populated atolls of the Marshall Islands and Kiribati, respectively, clearly demonstrate the distinction between the urban and rural zones on those 'capital' atolls.[21,23] On Majuro, the urbanized section around the eastern side of the atoll has been characterized by rapid population growth and intensive coastal development during the last few decades such that in 2011 it included about 50% of the total population of the Marshall Islands.[53] Analysis of shoreline changes over 40 years (from 1967 to 2006) showed that the urban islands expanded both toward the lagoon and onto the ocean-facing reef flat largely driven by causeway construction and reclamation for residential, commercial, and industrial activities including the international airport.[21] In contrast, the rural area in the west of Majuro has been subject to much less human modification and has much lower rates of shoreline change. While there have been pockets of both accretion and erosion on the rural lagoon shore, the latter now appears to predominate confirming an earlier trend.[54] On the other hand, accretion has been a consistent trend along the rural ocean-facing shores.[21]

Similarly on Tarawa, the capital atoll of Kiribati, the urban–rural distinction is also clear. Over 40,000 people live in the South Tarawa Urban District (STUD)[55] that comprises the islands strung along the southern reef, while the islands along the northeast rim make up the rural district of North Tarawa. Changes in shoreline position over 30 years (1968–1998) show that the total land area on the atoll has increased by nearly 20%, all in urban South Tarawa.[23] Reclamation of sandy intertidal areas of the lagoon, causeway construction between islands as well as seawall construction and backfill are the main reasons for the increase.[56] By way of contrast in rural North Tarawa, where population is sparse, 25 of the 40 islands were classified as 'stable' 13 islands showed net accretion and only two displayed net erosion over the 30-year period.[23]

Outer Islands: Key Sites for Sea-Level Rise Assessments

On the capital atolls, there is a clear distinction between urban areas and rural areas that is expressed in differences in the scale and causes of recent island and shoreline change. Even with downscaling of the 'urban' areas to village size—where resident populations are in the order of hundreds rather than thousands—there can still be a contrast between shores that are adjacent to permanent settlements and shores of islands that have no settlement. For instance on the main populated island Nukutoa (2007 population ~400) on Taku atoll (Papua New Guinea) seawalls constructed in front of the village in the 1970s provoked an accelerated loss of sandy beaches and reduction in beach width from about 10 to 3 m from 1943 to 2003.[26] Similarly on the Kiribati atolls of Maiana and Aranuka (population 1908 and 1158 in 2005)[55] village shores modified by groins, seawalls, and other structures had the unintended consequence of stopping or slowing sediment transfers resulting in local erosion, though elsewhere lagoonal shorelines were largely accretionary or stable from 1969 to 2009. During that 40-year period, low net rates of shoreline movement were reported, and although rates increased over the short term (2005–2009) the location of erosion, accretion, and stable shores was similar to the longer-term pattern. The greatest changes occurred near ends of the largest islands on both atolls, associated with longshore movement of coarse sand and gravel to build up spits and bars.[20]

On Wotje, an outlying atoll in the Marshall Islands ~300 km from the capital Majuro, the total population in 2011 was under 900,[53] most located on the largest island with little permanent habitation elsewhere. Between 1945 and 2010, net accretion was evident on 36 of the 52 islands with 'no significant change' on the other islands. Over a shorter and more recent period (2004–2012), several of the islands on Wotje were in an erosive state.[22] Similar long-term trends were also evident on uninhabited Nadikdik atoll in the southern Marshall Islands, where only two of 29 islands showed a decrease in island size between 1945 and 2010; 14 islands increased in area, the remainder being stable.[25] Comparable results were reported from two atolls in French Polynesia. Surface area changes of 41 islands on Manihi atoll (1961–2001) showed 67% of islands increased in area, 29% remained stable and only two islands reduced in area, while on Manaue atoll five out of the six islands showed a decrease in area between 1955 and 2008.[24] Within each atoll, island-change rates displayed distinct ocean- and lagoon-side trends that were not consistent either across the atoll or between atolls. Such complex patterns of change are a common conclusion of all of the studies to date and appear to be at odds with the presumption of extensive island erosion over the last few decades.

Collectively the shoreline-change data from both the whole-island studies summarized in Figure 4 and from the five other atolls in French Polynesia[24] Kiribati[20] and Papua New Guinea[26] listed in Table 1 support the view that sea-level rise has not been the primary factor controlling shoreline dynamics and change on atoll islands. Moreover, the observations from all study sites indicate that atoll islands have persisted over multidecadal timescales in a region of the Pacific that has experienced sea-level rise rates significantly higher than the global mean over the past several decades.[27–30]

FUNAFUTI AND THE 'SINKING ISLANDS'

Nowhere has the potential of sea-level rise to devastate a nation been more publicized than that relating to Tuvalu, and specifically to the atoll of Funafuti.[15,16,57–59] However, in many reports the distinction between Tuvalu, the country, and Funafuti, the atoll, is not always made clear.[60] Tuvalu, the island nation, comprises a chain of nine table reefs and atolls. There are however more than 100 islands in Tuvalu with over 30 on the capital atoll of Funafuti (see Figure 2(a)). Because Funafuti is the only atoll with an airport in Tuvalu, it is a popular venue for journalists and activists interested in observing and communicating the impacts of sea-level rise on atoll islands, especially during periods of predictable 'king tides'[60] when for example in February 2006 the media saw what it came to find: 'the new Atlantis'.[61]

On Funafuti, few visitors leave the major urban settlement located on the largest and boomerang-shaped island, Fogafale and its northern extension Tegako. Like most Type 2 islands,[45] Fogafale's surface topography is made up of a high seaward ridge that was described as a 'hurricane bank' over 100 years ago.[62] The 'hurricane bank' is separated from the lower lagoon shore ridge by an elongate depression that extends along the center of the island. Until 60 years ago, the central depression in the widest part of Fogafale was occupied by a mangrove swamp—the 'taisale'—most of which is now covered by the airfield built hurriedly during the Second World War in 1943 of coral shingle and rubble sourced primarily from excavating the low central depression to a level below that of mean sea level.[63] Not surprisingly, this low artificial corridor is especially conducive to flooding which is often cited as evidence of the effects of sea-level rise and confirmation that the 'islands are sinking'.[15,64] Rarely however is the form and origin of the flooded sites described or the fact that such flooding is not a new phenomenon. Indeed, the interior of Fogafale was subject to flooding in the mid-1890s and a reconstruction of conditions at a series of time-slices since then and through to the 21st century show that the island has been subject to a considerable degree of human modification, including urbanization, that has exacerbated the tidal inundation problem.[65]

In addition to the question of the relationship between inundation, 'king tides,' and sea-level rise,[60] Funafuti also provides an opportunity to review atoll

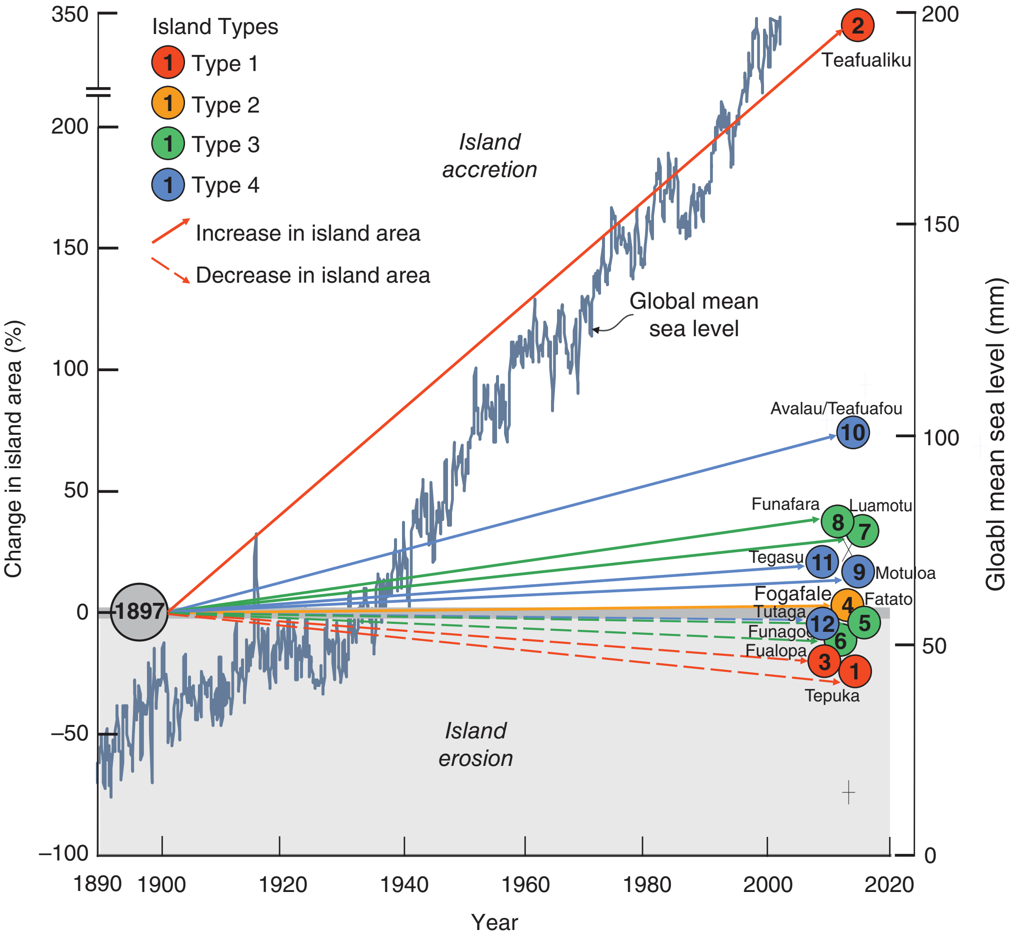

FIGURE 5 | Island area change (%) between 1897 and 2013 for a sample of 12 islands on Funafuti atoll, Tuvalu. The four island types located on the map of Funafuti atoll (Figure 2(a)) are color coded. The trend of global mean sea-level rise from 1890 to 2010 is also shown (see Figure 1(a)).

island response to rising sea level due to the existence of two temporally significant datasets. First, the atoll is located in a region of the Pacific that has experienced one of the fastest rates of sea-level rise over the past few decades (see Figures 1(b) and 3)[29,30] And second, a baseline survey of all of the islands on Funafuti was carried out more than a century ago that allows subsequent changes in island shorelines to be documented.[62]

A detailed study of planform changes of the islands on Funafuti atoll is in preparation using geological maps of the islands surveyed in 1897 during the second of three Royal Society Expeditions (1896–98) to Funafuti, vertical aerial photographs taken in the 1940s, 1970s, and 1980s, and satellite imagery in the 2005 and 2013.[66] The geological maps of over 30 islands published as 14 large scale (1:5000) colored map sheets still remain the most comprehensive and detailed illustrations of the surficial morphology of any atoll.[67] Interestingly, the prime authors of the maps, Australian geologists TW Edgeworth David, and George Sweet anticipated that the island maps of Funafuti atoll could serve as a baseline 'for later reference when possible changes on a larger scale in its physical geography and geology are being studied by future observers' (Ref 62, p. 89).

Here, we summarize the net changes from 1897 to 2013 of a sample of 12 islands on Funafuti atoll (see Figure 5). The sample covers all four types of atoll islands distinguished in the central Pacific[45] and includes the capital island of Fogafale as well as a number of smaller islands identified in Figure 2(a).

Results of the change in size (area) of the islands in 2013 relative to 1897 clearly shows that while some islands have increased in size, others have decreased. Contrasts in area change can be illustrated by two islands: Teafualiku and Tepuka (Figure 2(a), Box I). In 1897, there was practically no vegetation on Teafualiku except for three coconut palms,[68] an observation confirmed by the American naturalist Alexander Aggasiz who photographed the island in 1898.[69] In 2013, Teafualiku had a vegetated area of

0.23 ha, more than trebling its size since 1897. On the other hand, over the same time frame the larger nearby island of Tepuka decreased in area by 23%, with substantial erosion on the lagoon side where outcrops of beachrock are exposed indicating previous more stable shore positions. Despite this reduction in area, more than half of the original vegetated core (54%) of Tepuka still remains.[70]

Both Teafualiku and Tepuka are Type 1 sand islands on the northwest rim of the atoll. On the other hand, the islands along the eastern rim are composed predominantly of coral rubble on the ocean side and sandy sediments along the lagoon shore (Figures 2(a) and 5). Fogafale, the boomerang shaped—and largest—island (Type 2) has been stable over the last century (area increase 2.6%), while the elongate islands of Fatato through Luamotu (Type 3) show both decreases and increases, the former as a result of erosion of the ocean-facing shore and sediment wash-over on to the island surface and the latter from storm rubble accreting along the island ocean shores.[71] The rectangular rubble islands in the southwest of the atoll (Type 4) have generally increased in area and in one case neighboring islands have merged together to form a larger entity (Avalau-Tefoafou). Collectively, this sample of results reveals considerable differences in the magnitude and direction of island area change over the centennial timescale though there are hints that there is some integrity in the pattern of change within each island type (Figure 5). There are two other points relevant to the assertion that island erosion and destruction is an inevitable response to rising sea level. First, despite a period of accelerated sea-level rise reaching rates of ~5.1 mm/year over the past 60 years at Funafuti, there has been no unidirectional trend of erosion or consistent reduction in island area.[28,30,66] Second, all 32 islands mapped in 1897 are still present, including the smallest islands (<0.5 ha) though as illustrated in Figure 5 some have reduced in size, others enlarged.

DISCUSSION

Morphodynamics and Patterns of Island-Shore Change

The summary of Funafuti data are consistent with results from the other atoll islands that show no persistent erosional trend or constant decrease in island size in spite of the rising level of the sea.[29,30] This conclusion is contrary to many perceived notions and reports on the impacts of sea-level rise on atoll islands.[5,16,59] Instead both localized accretion and erosion have occurred, though the net effect over the last few decades has been primarily one of shoreline stability and secondarily accretion and island extension rather than erosion and island reduction. These results suggest that sea-level rise is not forcing unilateral shoreline erosion and that other factors play a more dominant role in island change. While on all 12 atolls instances of island erosion have been cited, generally these have been either of a temporary nature or have been offset by accretion around other parts of an island. It is often forgotten that the sedimentary products of island erosion—commonly skeletal sand and/or coral rubble—do not just disappear with erosion. Instead, they must go somewhere and in atoll situations there are five possibilities. The products are either: (1) transported off-reef into deep water; (2) moved along the island shore; (3) returned to the seaward reef flat; (4) deposited in the nearshore lagoon; or (5) transferred up onto the island surface. Only the first of these sinks results in permanent loss to the island sediment system, while the last adds to island elevation. Losses into the lagoon can be either temporary or permanent depending on the abruptness of the island-lagoon slope. Typically, the lagoon shore slope is quite gentle and together with on–offshore and longshore transport sediment can be constantly recycled between the island and adjacent reef and lagoon or around the island margin, the latter often on a seasonal basis.[10,72]

The results also demonstrate the morphodynamic nature of island shores. Three patterns of shoreline-change behaviour are identified. First, several kinds of shoreline movement are common, exclusive of human impacts: landward migration of ocean shorelines, lagoon-ward progradation, infilling of embayments and lateral extension of islands, spits, and forelands. Accretion of ocean-side ridges and lagoonal mangrove fringes, the formation of new islands, break up of single islands into several segments, and coalescence of two or three adjacent islands to form one larger entity have also been reported. Causes of these observed changes vary though not all of the studies identify causal mechanisms for the different styles of shoreline change. Cited climate–ocean processes that result in island accretion and/or erosion include trade wind wave action, distant-origin swell waves, short-term storms and surges, local autogenic shoreline processes, and ENSO-related factors. These processes all fit comfortably within the envelope of climate variability. Differences in island exposure and location both within and between atolls as well as the climate–ocean setting are shown to be important variables in determining the relative importance of the foregoing processes.

Second, the magnitude of short-term (yearly) changes has been greater than those over the longer term (decadal). This suggests that after some physical disturbance island shorelines strive to return to some more stable equilibrium that varies between the four atoll island types identified earlier (see Figure 2(a)). For instance, large storms or strong seasonal variations in erosion or accretion may result in extreme repositioning of the mobile beach that tends to return to its pre-storm or pre-season position following a fair-weather period.[73,74] In some cases, storm impacts may take years or even decades to propagate through the island system as indicated in the case of Nadikdik atoll, Marshall Islands by the ongoing response to the devastating typhoon of 1905.[25]

Third, shoreline behaviour over the last few years appears to differ from earlier trends though there is no consistency between the atolls. For instance, both the magnitude and direction of change are different in the following three examples. On Maiana and Aranuka in the four years 2005–2009, enhanced rates of instability were not influenced directly by sea-level change but could reflect a response to larger waves and stronger currents, or simply record greater shoreline variability around some dynamic mean.[20] On Wotje atoll, the post-2004 shift away from long-term accretion may indicate natural shoreline dynamism, a transition toward erosion, or be the product of the short-term record that potentially favors the presence of erosional scarps and fallen vegetation over the slower accretionary built berms and reestablishment of strand vegetation.[22] In contrast on Taku atoll, the long-term decrease in median beach width for most islands (averaging −4.7 m from 1943 to 2003) was reversed in the last decade with beach width remaining stable or showing only minor upward and downward trends probably resulting from local controls on sediment redistribution by longshore currents.[25] In all three instances, the cause of the recent trend change is not uniform, or is the cause clear, though sea-level rise is not considered as the primary mechanism.

Attribution and Misattribution

If the role of sea-level rise in contributing to shoreline change on atoll islands over the last few decades is ambiguous, the same cannot be said for human impacts. On both Majuro and South Tarawa, changes in island area and shoreline position have been unequivocally attributed to human activities.[21,23] Reclamation, construction of seawalls, groins, and causeways between islands have resulted in large increases in local island area and have also altered patterns of sediment movement creating foci of accumulation and erosion. On some island shores, erosion is amplified by sand and aggregate mining of beaches and reefs.[13,24,26] In such circumstances, it is not surprising that any potential impact of sea-level rise is masked by the more pervasive anthropogenic effects. Thus, detection and attribution of sea-level rise impacts is particularly challenging especially in the constrained environments of atoll islands where human impacts are magnified and there is a strong influence of climate variability.[75,76]

Failure to recognise the contribution of natural variability and direct human modification of atoll island shorelines and structures has lead to misattribution of seasonal inundation and erosion hotspots to recent sea-level rise. Though not acknowledged as such, that relationship is a spurious one. However, it has gained a great deal of attention and is especially highlighted in the media[57] and by international political considerations that are often featured in emotive ‘side’ events at UNFCCC meetings such as at COP15 in Copenhagen.[77] In these cases, misattribution is used to support the view that atoll islands—and nations—will disappear beneath the sea through accelerated shoreline erosion as a consequence of the ongoing and future rise of sea level.[78] A counter view is that erosion of island shorelines ‘is far more likely to result from local or proximal causes (such as a particular storm) than to be attributable to the imperceptible gradual subsidence or steric sea-level rise’ (Ref 13, p. 90). Clearly the studies reviewed here provide little evidence of widespread erosion or constant decrease in island size in response to the rising level of the sea over the last few decades. Rather, they show localized erosional and depositional trends that demonstrate the dynamic nature of island margins and that the main agents of substantial change have been from human activity and climate–ocean variability, not sea-level rise.

TOWARD 2100: POTENTIAL IMPACTS ON ATOLL ISLANDS

There is little doubt that global sea level will continue to rise and that there will continue to be strong regional differences in its magnitude and timing. Based on RCP scenarios, the IPCC AR5 projects global sea-level rise for the period 2081–2100 (compared with 1986–2005) will likely range from a low of 0.26–0.54 m (RCP 2.6) to 0.53–0.97 m (RCP 8.5) with an expectation of an increase in occurrence of future sea-level extremes primarily related to the increase in mean sea level.[79] Changes in ocean wave conditions will also affect the atoll archipelagos. Mean significant wave height (defined as the average of the highest one-third of wave heights) is projected to be 5–10% higher than the present day mean in the tropical South Pacific and the Southern Ocean by the end of the 21st century.[79,80]

Projecting how atoll islands will physically respond to future rises in mean and extreme sea level, changes in wave conditions and human-induced pressures, as well as to increases in cyclone intensity, sea surface temperature, and ocean acidity is a critical but complex issue.[9,13,81] It is also an issue that is 'poorly resolved' although there have been several recent reviews of the implications of the projected reef ecosystem changes on the stability and maintenance of coral reef islands. These suggest that future degradation of reef ecosystems may not result in an immediate or significant decline in net production and availability of sediment to nourish reef islands at least of noncoral taxa.[9,81] Differences in the timescales of adjustments between reef health and geomorphic response are distinctly nonlinear such that any short-term change in reef health takes time to propagate through the geomorphic system and ultimately to be expressed at island shores. Moreover, geomorphic impacts expressed in terms of sediment supply are likely to be more subtle than the dramatic loss of ecological services associated with reef decline.[82,83] Thus, given the uncertainties associated with linking projected climate–ocean conditions including sea-level rise to atoll island shore changes, retrospective studies can provide some evidence-based insights into what can be reasonably expected in the future, at least until the first half of the next century.[5]

While we must be cautious about extrapolating results from the studies of historical and recent shoreline behaviour and island change reviewed here, when added to our more extensive knowledge of atoll island formation and dynamics, and our understanding of the relative roles of physical and human impacts on coastal systems, there is a defensible basis for making an assessment about future island stability. Although the argument that sea-level rise drives some degree of morphological change can be justified, to date no study has been able to quantify that impact, even in relative terms. This is either because: (1) the role of sea-level rise has been dwarfed by other change processes; or (2) because the impact of sea-level rise is less significant than previously envisaged. It also suggests that atoll islands are robust rather than fragile systems, a point emphasized by several other independent studies.[13,84]

Destruction or Persistence of Atoll Islands?

By the end of the 21st century, we expect the majority of the present atoll islands in the central and western Pacific to be still there, providing the scale of future climate–ocean processes does not accelerate much beyond those projected in the IPCC Fifth Assessment.[76,79,85] While some islands may reduce in size, it is likely there will be an equal or greater number that remain the same size or increase in area if present trends continue. Justification for this view is based on an appreciation of the modes of sediment supply, atoll island formation and geomorphic development through time.[9,37,45] It is also based on results from this review of actual decadal-scale island changes in a region of accelerated sea-level rise and on our earlier characterization of atoll island types (Figure 2(a)).

Most Type 1 islands are in nodal positions where refracted waves converge in response to roughly circular or oval reef shapes.[86,87] Sediments get trapped in these nodes that tend to be relatively stable features particularly on the leeside of Pacific atolls. On these refraction-controlled locations, sediments are generally sandy and the islands have built up through incremental accretion.[13,45] While central cores remain intact island margins are quite mobile and quickly adjust their size, shape, and position to any changes in boundary conditions.[70] On the other hand, Type 2 islands on the 'corners' of atolls and Type 3 islands on the long and narrow reefs on the exposed windward sides of atolls are generally L- or boomerang shaped or elongate with a high seaward ridge of coral gravel or rubble. Often there is a series of parallel linear ridges that indicate episodic storm accretion of the ocean shore in the shadow of which finer lagoonal sediments are deposited. Such bidirectional forces provide a measure of stability to both the core and margins of these islands. On Type 4 islands, stability is also provided by the coral boulder sediments, high elevation, and volume of island sediment overlying the resistant conglomerate foundations.[9,13,45] Thus, for different reasons each of the four atoll island types have a measure of resilience, tend toward an equilibrium condition and in our view will continue to do so in the coming decades.

Sustainable Islands Need Sediment

Central to the ability of atoll islands to persist as sea-level rises is the maintenance of an adequate supply of sediment, of suitable type and grade, for transport to and incorporation within island structures.[9,88] That supply can come from either fresh sediment produced on the adjacent reef and lagoon or it can come from reworking of the shore deposits of existing islands. On many Pacific atolls, islands were built when sea level was higher than present between 5000 and 2000 years ago, and since then they have maintained their essential dimensions through recycling extant shore deposits supplemented by episodic injections of sediment from tropical cyclone waves, tsunami, and distant-source swell. As a consequence of the sea-level fall in the last two to three millennia, the present seaward reef flat on most Pacific atolls is an intertidal platform emergent at low water. Sediment production by coral is minimal on these intertidal surfaces with live coral and its sand and gravel producing community restricted to sub-tidal depths. However, on many intertidal reefs secondary sediment producers such as foraminifera, coralline algae, molluscs, and *Halimeda* are the primary sediment providers and major contributors to island building (see Ref 88; Figure 5). Those sediment production 'factories' and a clear transport path from source to sink are essential for the ongoing sustainability of islands. There are several implications of these sediment production regimes and delivery routes. First, the future ability of islands to accrete and build vertically will rely on continuity of sediment supply—even if episodic—that is likely to vary between locations as a function of the availability of different contributing organisms. It may also vary in response to the differential impacts of increasing ocean acidity and sea temperature and to the increasing intensity of tropical cyclones.[85] While it is tempting to suggest a downturn in net sediment production from the predicted reduced rate of calcification of corals and coralline algae as a result of increasing ocean acidification, those conditions are also expected to trigger increased carbonate dissolution, weaker skeletal structures, and a shift from reef building to reef erosion, potentially providing easier recruitment of sediment available for delivery to island shores through the increased intensity of tropical cyclones.[9,89]

Second, the reef to island, or lagoon to island, sediment transport paths need to be kept clear. But such a link is not possible in many parts of those intensively settled islands that have seawalls and other shore defenses that impede sediment transfer.[56,75] Third, with sea-level rise an increase in water depth across the reef surface can be expected to result in vertical accretion of corals and their associated communities[90] that could provide a renewed source of sediment for island maintenance or growth.[44,91] This is a possibility on Pacific atolls where future sea-level rise may release the vertical constraint on reefs that has been present since the sea-level fall following the mid-Holocene.[91,92] Fourth, as island beaches are truncated at the solid reef-flat surface (see Figure 2(c)), perched beach dynamics rather than those developed for continuous unconsolidated beach-nearshore sediments should be adopted in modeling atoll island building or destroying processes.[9,88]

Sustainable Islands Need Accommodation Space

There also needs to be accommodation space for islands to grow outwards and increase in size (area) to accommodate any extra available sediment.[92,93] As the case studies have demonstrated, accommodation space is limited on those islands with seawalls and shore protection structures,[56] but it may become available on the windward side of other islands, where through shore-face erosion and wash-over, the seaward shoreline moves island-ward or lagoon-ward and leaves a vacant space along the ocean shore. That space is available for further accumulation of sediment such as that deposited by Hurricane *Bebe* along the eastern reef of Funafuti atoll in October 1972.[71] Similarly, where the level of the reef flat is continuous between islands, and not separated by channels or *hoa*[94] adjacent islands can join together increasing the area of the formerly separate islands. Nadkidik atoll in the Marshall Islands provides several examples of island welding between 1945 and 2010 (see Figure 4).[25]

On atoll islands, there is also accommodation space available to grow upwards, to increase island elevation. But processes to lift sediment and emplace it on top of the island surface are required. Storm wave run-up and tsunami over-wash can satisfy that requirement. There is abundant evidence under present sea-level conditions, to show that fresh sediment derived from the adjacent reef or from shore erosion has been deposited onto island surfaces. Elevated sea levels and wave action associated with the 2004 Sumatran tsunami in Maldives and long period swells generated by far-field north Pacific storms in 2008 that reached Taku atoll, Papua New Guinea resulted in emplacement of new layers of sediment covering and elevating island surfaces.[95,96] With higher sea levels in the future, the reach of such waves can be expected to increase vertically to maintain the relationship between island elevation and sea level.

THE CHALLENGE AHEAD: CHANGING ADAPTATION PRIORITIES FOR ATOLL STATES

The results of our analysis of shore and island change over the past several decades provide a less pessimistic future for the atoll nations and islands reviewed here in relation to ongoing sea-level rise. They also provide a formidable challenge to governments, international agencies, and aid donors that requires a paradigm shift away from the popular narrative of the last few years that simply reads: sea-level rise results in island inundation, erosion, and destruction and ultimately island abandonment and out-migration of people. That message is an inappropriate one and, as several reports have indicated, undermines the development of constructive adaptive pathways that build resilience in island communities.[97–99] Instead, there are a number of lessons learned from our analysis that can be used to guide adaptation policy and practice in the future.

First, it is likely that virtually all of the present atoll islands will be there at the end of the 21st century if present trends continue. They are unlikely to disappear or sink beneath a rising water level as has been asserted during the last decade or so. Thus, an emphasis on external migration as a key climate change adaptation strategy cannot be justified on grounds of sea-level rise alone (though there may be economic, social, or cultural reasons for resettlement as there has been in the Pacific's past).[14,61] On the capital islands, there may well be limits to habitability unless population increases and the flow of people from outer islands are stemmed, or firm measures to improve environmental conditions and shore protection practices are put in place as has been recommended on so many occasions in the past.[14,75,100,101] Moreover, external migration is not universally endorsed by the Pacific atoll nations themselves as exemplified by recent differences in approach by the governments of Kiribati and Tuvalu.[102]

Second, we can expect big differences between how islands respond to future changes in climate–ocean boundary conditions including sea-level rise. Differences will result from several factors including atoll location within the Pacific basin, and the exposure of individual islands to the relative forces of trade wind seas, tides, westerly monsoon waves, deep ocean swell, and tropical storm waves as well as the differential impact of increases in ocean temperature and acidity on island sediment sources.[24,81] Differences in other local factors such as sediment caliber, composition and elevation of an island, its geometry and size, and the amount of consolidated or unconsolidated material will also influence island response.[45,88] Islands composed of coarse sediments such as coral rubble, high wide islands, and those with outcrops of cemented beachrock or conglomerate are likely to be more resilient than those made up of sand,[9] of unconsolidated sediment,[13] or narrow low islands.[40] There are three implications of this variety of island characteristics, atoll settings, and possible vulnerability. (1) It is clear that a 'one-size fits all' adaptation strategy is not going to capture the diversity of atoll island types and climate–ocean settings; (2) governments could identify islands that are more susceptible (or resistant) to change than others and the reasons for that susceptibility (or resistance); (3) they could also engage more fully in increasing efforts to quantify their land and shore resources, identify the rates, magnitudes, and causes of island and shore change and include an assessment of both natural and human impacts and how those impacts—if negative—can be reduced. The case studies cited in this review provide examples of how this can be done.

Third, over the last two or three decades, there has been a large number of vulnerability and adaptation studies in the Pacific's oceanic islands and no shortage of policy options and planning recommendations.[101] But implementation and enforcement has been an ongoing problem particularly in the capital atolls where recent influxes of people from the outer islands has put enormous pressure on local infrastructure and services.[95] The continued expansion of urban islands through reclamation and erecting shore protection measures to seaward is in need of critical examination, not only from the perspective of sustainability but also of increasing vulnerability.[13,14,21] For instance, there has been a recent and uncontrolled boom in private coastal development including reclamation projects and coastal defenses on the capital atolls[21,54,56] though early warnings of the negative impacts of such developments were made more than 20 years ago.[75] It is these areas where the negative impacts of ongoing sea-level rise are likely to be most acute. The present situation calls for a coherent plan that addresses the inadequacy of environmental regulations and enforcement to avoid what one author has called—with reference to South Tarawa—the coming environmental 'perfect storm'.[103]

Fourth, it is likely that such projects will become increasingly unsustainable into the future because of constraints on the availability of suitable local aggregate and the adverse environmental consequences along adjacent ocean or lagoon shores including increased shoreline instability. Appropriate adaptation measures, such as incorporating coastal processes, seasonal wave, tide, and storm variability as well as sea-level rise are required when designing reclamation and protection structures and developing appropriate management plans.[21,23] Concerted efforts to reduce the damaging impacts of human activities will be needed including prohibiting the extraction of sand and coral rubble from beaches and reefs in close proximity to settlements.[23,54,75]

Fifth, there is however a positive side to the movement of people from the outer islands to the main urban centers. In Tuvalu, the Marshall Islands, and Kiribati, many of the outer islands have experienced population declines.[53,55] Fewer people mean reduced pressure on ecosystems, reefs, water resources, and subsistence food supplies, thus increasing sustainability of islands away from the capital atolls.[104,105] Such islands, as well as the other sparsely inhabited larger islands, can serve as a national safety valve for internal resettlement within atoll nations. To date, this alternative—internal resettlement as an adaptation measure—has not been raised in government or agency reports or in academic treatises. Planning for such an eventuality has to start early and should involve at least four considerations:

1. Encouragement and funding for island habitability research along the lines of the socioeconomic and land resources surveys carried out in Kiribati and Tuvalu in the 1970s and 1980s.[106,107]
2. Consider lessons learned from recent experiences of moving island people to new locations within their own country that has created new vulnerabilities for the communities in the Solomon Islands[108,109] and in the Maldives where the Safe and Safer Islands program[110] failed due to the fear of losing traditional village culture.[111]
3. Review of present land codes to recognise: (a) contemporary and future shoreline changes and trends; and (b) potential adaptation strategies that include problematic land tenure issues that are rarely raised in-country such as those relating to 'neglected lands' and 'absentee ownership'.[107,112,113]
4. Address resettlement issues in the national legal framework to identify areas where legal or policy changes are required.[2,114] While it has been argued that resettlement does carry a high risk of maladaptation, full knowledge of the potential social and environmental outcomes at both the origin and destination island can be assessed.[98,108,115]

Finally, in the Pacific atoll nations discussed here, as well as in the Maldives in the Indian Ocean, there are many more rural, uninhabited, or infrequently visited islands than those that have permanent settlement. As suggested above, these outlying islands can serve as 'control' sites where natural processes can be left to dominate over those associated with direct human activities and where shoreline changes can be monitored in the future. Unlike the urban islands where planned adaptation actions are essential, any government or community adaptation policy for the outer and rural islands should be based on allowing, not impeding, the natural shoreline system to adapt autonomously. For in the long run, it may be these outer islands, away from the capital atolls and urban islands that could provide the most secure homes for future generations of atoll residents.

CONCLUSION

Sequential island area and shoreline position changes over the last few decades have been analyzed on over 200 reef islands on 12 atolls in the western and central Pacific. During that time, sea level has risen in the region at rates three to four times greater than the global average. Contrary to expectations, this has not resulted in widespread erosion or the disappearance of atoll islands. Indeed, islands have persisted in the face of this sea-level rise, and many have increased in surface area and elevation by natural processes. But the persistence of islands does not mean that they are not changing their size, shape, and position. Instead, island margins are continually adjusting to normal seasonal erosion and accretion processes, to episodic extreme events and to variations in sediment supply. To date the impact of this normal range of environmental conditions appears to predominate over any long-term morphological trend or signal related to sea-level rise. Indeed, it can be argued that those conditions are necessary for the ongoing sustainability of atoll island morphology.

The results of our analysis are also encouraging. They demonstrate that atoll islands are not the fragile landforms that are sinking or eroding away, but instead they are rather robust features that have responded to large increases in sea level and a whole range of climate–ocean and human forces with little net loss of island area over the last several decades. Our analysis also suggests that the challenge for atoll nations into the future is to develop flexible adaptation strategies that: accept the likely persistence of their islands over the next century; acknowledge that sea-level rise is just one of a series of multiple stressors; recognize the different island types that make up the country; accommodate the ongoing dynamism of island margins; and, affirm the importance of the rural and outer islands as a major potential resource.

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