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FOCUS ARTICLE

A global assessment of atoll island planform changes over the past decades

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Over the past decades, atoll islands exhibited no widespread sign of physical destabilization in the face of sea-level rise. A reanalysis of available data, which cover 30 Pacific and Indian Ocean atolls including 709 islands, reveals that no atoll lost land area and that 88.6% of islands were either stable or increased in area, while only 11.4% contracted. Atoll islands affected by rapid sea-level rise did not show a distinct behavior compared to islands on other atolls. Island behavior correlated with island size, and no island larger than 10 ha decreased in size. This threshold could be used to define the minimum island size required for human occupancy and to assess atoll countries and territories' vulnerability to climate change. Beyond emphasizing the major role of climate drivers in causing substantial changes in the configuration of islands, this reanalysis of available data indicates that these drivers explain subregional variations in atoll behavior and within-atoll variations in island and shoreline (lagoon vs. ocean) behavior, following atoll-specific patterns. Increasing human disturbances, especially land reclamation and human structure construction, operated on atoll-to-shoreline spatial scales, explaining marked within-atoll variations in island and shoreline behavior. Collectively, these findings highlight the heterogeneity of atoll situations. Further research needs include addressing geographical gaps (Indian Ocean, Caribbean, north-western Pacific atolls), using standardized protocols to allow comparative analyses of island and shoreline behavior across ocean regions, investigating the role of ecological drivers, and promoting interdisciplinary approaches. Such efforts would assist in anticipating potential future changes in the contributions and interactions of key drivers.

This article is categorized under:
Assessing Impacts of Climate Change > Observed Impacts of Climate Change
Paleoclimates and Current Trends > Earth System Behavior

KEYWORDS

Atoll islands, attribution, climate change, planform changes, vulnerability

1 | INTRODUCTION

Atolls are ring-shaped reefs occurring in mid-ocean, which generally form linear chains (Woodroffe & Biribo, 2011). The atoll rim encloses a central lagoon and supports reef islands composed of unconsolidated or poorly lithified carbonate sand and gravel deposited on the reef platform by waves and currents (McLean, 2011). Since the late 1990s-early 2000s, the extent to which these low-lying (generally <5 m) islands are susceptible to be physically destabilized by climate change has become a major global concern, as their destabilization would eventually cause the disappearance of entire nations (e.g., the Maldives, Tuvalu, and Kiribati), due to reef islands constituting the only habitable area in these countries (Barnet & Adger, 2003; Connell, 2003; Dickinson, 2009; McAdam, 2010; Nurse et al., 2014). Climate-ocean related changes, including sea-level rise, increasing wave energy, change in tropical cyclone frequency or intensity, and ocean warming and acidification, are considered as major threats to these islands' persistence, as the surrounding reef ecosystem may lose the capacity to fulfill its major functions, that is, provide sediments to islands and buffer storm waves (Albert et al., 2016; Becker et al., 2012; Chand, Tory, Ye, & Walsh, 2016; Church et al., 2013; Ferrario et al., 2014; Gattuso et al., 2015; Hughes et al., 2017; Mentaschi, Vousdoukas, Voukouvalas, Dosio, & Feyen, 2017; Perry & Morgan, 2017; Shope, Storlazzi, & Hoeke, 2017; Van Woesik, Golbuu, & Roff, 2015). Furthermore, recent modeling studies highlighted that future increased wave activity under sea-level rise may increase the frequency and extent of marine inundation on these islands in the event that coral reefs would not keep up with sea-level rise. This would cause increased soil and freshwater lens salinization, which would in turn affect water and food supply, thereby posing a threat to island habitability (Beetham, Kench, & Popinet, 2017; Gingerich, Voss, & Johnson, 2017; Shope, Storlazzi, Erikson, & Hegermiller, 2016; Storlazzi, Elias, & Berkowitz, 2015; Vitousek et al., 2017; Werner, Sharp, Galvis, Post, & Sinclair, 2017).

Since 2010 (Webb & Kench, 2010), a growing number of studies have assessed recent past-to-present (from the end of the 19th century to the 1990s–2010s) island planform changes to determine if atoll islands were contracting as a result of accelerating sea-level rise. McLean and Kench (2015) completed the first review on atoll island planform change, based on a 244-island sample from 12 Central and Western Pacific atolls distributed among six atoll countries and territories, that is, Tuvalu, Kiribati, the Federated States of Micronesia, the Marshall Islands, French Polynesia and Papua New Guinea. Using available quantitative data for 146 islands, they showed that despite the high rate of sea-level rise observed in this area of the Pacific (up to 5.1 mm/yr in Tuvalu over the 1950–2009 period), all of the sample islands had persisted, with, respectively, 72.6%, 19.2%, and 8.2% of islands exhibiting areal stability, expansion, and contraction. They concluded that climate-ocean variability, sediment production, and human activities were the major controls on island change, and stressed that the maintenance of an adequate sediment supply, of unobstructed sediment transport pathways and of sufficient accommodation space at the coast were the conditions required for island persistence over the 21st century. In line with these findings, they emphasized the major importance of considering in-country resettlement (vs. external migration) as a major adaptation strategy for atoll countries and territories.

Since this first review, new studies were carried out in the Pacific and Indian Oceans, which increased the documented sample to 35 atolls and 852 islands (666 and 186 in the Pacific and Indian Oceans, respectively). This extended atoll island dataset offers the opportunity to provide an updated review on atoll island multidecadal to centennial planform change, and to address three key questions: (1) Does atoll island behavior show regional or subregional variations in accordance with the rate of sea-level rise? (2) What is generic (i.e., global) and what is specific (i.e., regional to local) in recent atoll island and shoreline change? (3) What are the respective contributions of climatic, ecological and anthropogenic drivers to regional-to-local variations in island areal change?

Beyond addressing these questions, this article discusses future research needs and the implications of this review's insights for adaptation policies in atoll countries and territories.

2 | RECENT ATOLL ISLAND AND SHORELINE CHANGE

2.1 | Building an Atoll Island database

This article relies on the reanalysis of available data on recent past-to-present atoll island planform changes (Table 1), based on the elaboration of an *Atoll Island Database* (see Table S1, Supporting Information). First, we selected, in a comparative perspective, the papers based on multidate image analysis using standard shoreline change indicators, such as the base of the beach, and the vegetation or stability line (Duvat & Pillet, 2017; Ford, 2012; Webb & Kench, 2010). Second, we extracted from these papers (a) the metadata of documented islands, that is, country or territory in question, atoll name and geographic coordinates, island reference (name or number), timespan and duration of the period of analysis, current island size, and shoreline proxy used; (b) quantitative data, namely the net and decadal rates of change in aggregated atoll-wide and island land area, these two indicators being the only common ones between studies. In line with recent studies (Duvat & Pillet, 2017; Duvat, Salvat, & Salmon, 2017; McLean & Kench, 2015), we used the ±3% threshold to interpret atoll and island areal change, considering that change less than 3% ($-3\% < x < +3\%$) was not significant, while change $\geq 3\%$ and $\leq -3\%$ corresponded to an increase and decrease in land area, respectively. Within the limits of the data provided by the selected papers, we enriched the database with data on changes in shoreline and island position, and in island planform configuration (aggregation vs. break up, formation vs. disappearance, rotation). Lastly, we extracted from the reviewed papers and reported in the database the factors to which observed changes were attributed. These factors were classified into three categories (a):

TABLE 1 Current knowledge on multi-decadal island and shoreline change on atolls

Country or territory	Atoll or island (for patch reefs)	No. of islands	Timeframe considered		Shoreline proxy used	Authors
			Period	No. of years		
Pacific Ocean						
Tuvalu	Funafuti 8°S 179°E	26	1896/1998–2013	115–117	VL	Kench, Thompson, Ford, Ogawa, and McLean (2015)
	Nanumaga 6°S 176°E	7	1971–2014	43	VL	Kench, Ford, and Owen (2018)
	Niulakita 10°S 179°E	1	1971–2014	43	VL	Kench et al. (2018)
	Niutao 6°S 177°E	1	1971–2014	43	VL	Kench et al. (2018)
	Nui 7°S 177°E	13	1971–2014	43	VL	Kench et al. (2018)
	Nukufetau 7°S 178°E	26	1971–2014	43	VL	Kench et al. (2018)
	Nukulaelae 9°S 179°E	19	1971–2014	43	VL	Kench et al. (2018)
	Vaitupu 7°S 178°E	8	1971–2014	43	VL	Kench et al. (2018)
	Total	101	–	–	–	–
Marshall Islands	Majuro 7°N 171°E	15	1967–2004/2006	37–39	VL	Ford (2012)
	Wotje 9°N 170°E	49	1945–2010/2012	65–67	VL	Ford (2013)
	Ebon 7°N 168°E	19	WWII/1970–2010	40–65	VL	Ford and Kench (2015)
	Lae 8°N 166°E	15	WWII/1970–2010	40–65	VL	Ford and Kench (2015)
	Likiep 9°N 169°E	56	WWII/1970–2010	40–65	VL	Ford and Kench (2015)
	Rongerik 21°N 167°E	11	1970–2010	40	VL	Ford and Kench (2015)
	Ujae 9°N 165°E	9	WWII/1970–2010	40–65	VL	Ford and Kench (2015)
	Wotho 10°N 165°E	15	WWII/1970–2010	40–65	VL	Ford and Kench (2015)
	Palmyra 0°5′N 162°W	30[a]	1874/1947–2000	53–126	HWM	Collen, Garton, and Gardner (2009)
	Total	245	–	–	–	–
Kiribati	Tarawa 1°N 173°E	48	1968–1998	30	VL + BB	Biribo and Woodroffe (2013)
	Maiana 1°N 173°E	20[a]	1969–2009	40	BB	Rankey (2011)
	Aranuka 0°N 173°E	6	1969–2009	40	BB	Rankey (2011)
	Total	74	–	–	–	–
Federated States of Micronesia	Mokil 6°N 159°E	3	1944–2006	62	VL	Webb and Kench (2010)
	Pingelap 6°N 160°E	3	1944–2006	62	VL	Webb and Kench (2010)
	Total	6	–	–	–	–
French Polynesia, Tuamotu Archipelago	Manihi 14°S 145°W	41	1961–2001	40	VL	Yates, Le Cozannet, Garcin, Salai, and Walker (2013)
	Takapoto 14°S 145°W	49	1969–2013	44	SL + BB + CD	Duvat and Pillet (2017)
	Rangiroa 15°S 147°W	8	1969–2013	47	SL + BB	Duvat, Salvat, and Salmon (2017)
	Tikehau 14°S 148°W	14	1962/1981/1998–2014	16–52	SL + BB	Duvat, Salvat, et al. (2017)
	Mataiva 14°S 148°W	13	1976–2013	37	SL + BB	Duvat, Salvat, et al. (2017)
	Takaroa 14°S 145°W	76	1976–2013	44	SL + BB	Duvat, Salvat, et al. (2017)
	Total	201	–	–	–	–
French Polynesia, Society Islands	Manuae 16°S 154°W	6	1955–2008	53	VL	Yates et al. (2013)
	Tupai 16°S 151°W	5	1955–2001	46	VL	Le Cozannet et al. (2013)
	Tetiaroa 17°S 149°W	12	1955–2002	47	VL	Le Cozannet et al. (2013)
	Total	23	–	–	–	–
Papua New Guinea	Taku 4°S 157°E	16	1943–2012	69	VL + BB	Mann and Westphal (2014)
Total	Pacific Ocean	666	1896–2014	16–117	–	–
Indian Ocean						
Maldives	Huvadhoo 0°N 73°E	184	1969–2004/2006	35–37	VL	Aslam and Kench (2017)
Scattered Islands	Glorieuses 11°S 47°E	1	1989–2003	14	VL + BB	Testut et al. (2016)
Chagos	Diego Garcia 7°S 72°E	1	1967–2005	38	VL	Hamylton and East (2012)
			1963–2013	50	BS-WS	Purkis, Gardiner, Johnston, and Sheppard (2016)
Total	Indian Ocean	186	1963–2013	14–50	–	–

(Continues)

TABLE 1 (Continued)

Country or territory	Atoll or island (for patch reefs)	No. of islands	Timeframe considered		Shoreline proxy used	Authors
			Period	No. of years		
Pacific and Indian Oceans						
Total	All atolls/patch reefs	852	1896–2014	14–117	–	–

Note. The third column indicates the number of documented islands, which does not necessarily correspond to the total number of islands of the atoll. BB: base of the beach; BS-WS: brown soil-white sand limit; CD: inner limit of cyclonic deposits; HWM: high water mark; VL: vegetation line; SL: stability line; WWII: Second World War.

[a] Indicates that the number of islands was extracted from DigitalGlobe images provided by Google Earth, as it was not indicated by the authors of the reviewed papers. For atolls that were covered by several studies, only the most complete study is cited. See Table S1 for detailed results.

climate-ocean related drivers, including seasonal swell waves, climate variability (tropical cyclones, distant-source swells and ENSO phases) and climate change impacts (especially sea-level rise); (b) ecological drivers, including the reef ecosystem, and the native coastal and intertidal vegetation; and (c) anthropogenic drivers, that is, human-induced changes to atoll and island configuration and to island dynamics.

The *Atoll Island Database* includes 35 atolls and 852 islands, providing quantitative data on recent (i.e., past decades to century) change in land area for 30 atolls (29 in the Pacific and 1 in the Indian Ocean) and 709 islands, 533 of which are located in the Pacific and 176 in the Indian Ocean (Figure 1, Table S1). The territories having the highest number of documented islands are the Marshall Islands (245 islands), French Polynesia (224), and the Maldives (184). Of note, in the study areas, the average rate of sea-level rise over the past decades ranged from 2.0 ± 0.6 (Pingelap, Mokil; Becker et al., 2012) to 5.1 ± 0.7 (Funafuti; Becker et al., 2012) mm/yr (multiplier factor of 2.5), with most values falling between 2 and 3 mm/yr (Figure 2).

2.2 | Change in atoll and in island land area

2.2.1 | A global trend: The persistence of atoll and island land area

Over the recent past, 29 atolls exhibited a stable land area, while one (South Tarawa, Kiribati) increased in size (Figure 2). Collectively, these atolls comprise 709 islands, 518 of which were stable (representing 73.1% of islands), while 110 (15.5%) increased and 81 (11.4%) decreased in size. In total, 88.6% of islands were either stable, or increased in size (Figure 3, Table S1). These results show that atoll and island areal stability is a global trend, whatever the rate of sea-level rise. Tuvaluan atolls affected by rapid sea-level rise (5.1 mm/yr; Becker et al., 2012) did not exhibit a distinct behavior compared to atolls located in areas showing lower sea-level rise rates, for example, the Federated States of Micronesia or Tuamotu atolls (Figure 2).

2.2.2 | Regional and subregional variability in atoll and atoll island behavior

Despite island areal stability was the general trend, the Maldivian islands appeared more affected by erosion than the Pacific islands (Figure 2). Over the past decades, 70.5% of Huvadhoo islands (i.e., 124 islands) were stable, while 23.3% (41 islands) decreased and 6.2% (11 islands) increased in size. Over the same period, 73.9% of Pacific islands (i.e., 394 islands) were stable in area, while 18.6% (99 islands) increased and 7.5% (40 islands) decreased in size. Although data on Indian Ocean islands are still too limited to allow the detection of regional (Pacific vs. Indian Ocean) and subregional (e.g., Maldives vs. Chagos or Seychelles atolls) variations, these results nonetheless indicate that island behavior is not uniform on these atolls.

The extended dataset available for the Marshall Islands (8 atolls) and for French Polynesia (9 atolls) revealed the absence of homogenous atoll behavior within Pacific Ocean subregions. Within these two atoll groups, high between-atoll variability was recorded over distances of tens to hundreds of kilometers (Figure 2). For example, in the Marshall Islands, while on Majuro most islands (9/15) increased in size, the other atolls mainly showed island areal stability, with a variable proportion of islands that were stable, increased or decreased in size. Likewise, in the northern and north-western Tuamotu Archipelago, Manihi and Takaroa exhibited a high number of islands (15/41 and 13/68, respectively) that increased in area, while Takapoto and Mataiva predominantly showed island areal stability (noted on 21/26 and 11/13 islands, respectively).

2.2.3 | Correlation between the rate of change and island size

Generally, island behavior correlates with island size (Figure 3). First, the smallest islands (<5 ha), which represent 52.90% of islands (375/709), exhibited the highest variability in land area change, compared to larger islands. In the Pacific, 8 islands of this category exhibited a decadal rate of change ≥20%. Likewise, in the Indian Ocean, on Huvadhoo, areal gains or losses reaching up to ±20% were only experienced by very small islands (<1 ha). The highest and lowest rates of change were respectively of +125.5% for Lokejbar (3.3 ha) on Majuro and of −22.7% for a tiny island of Huvadhoo. In contrast, the

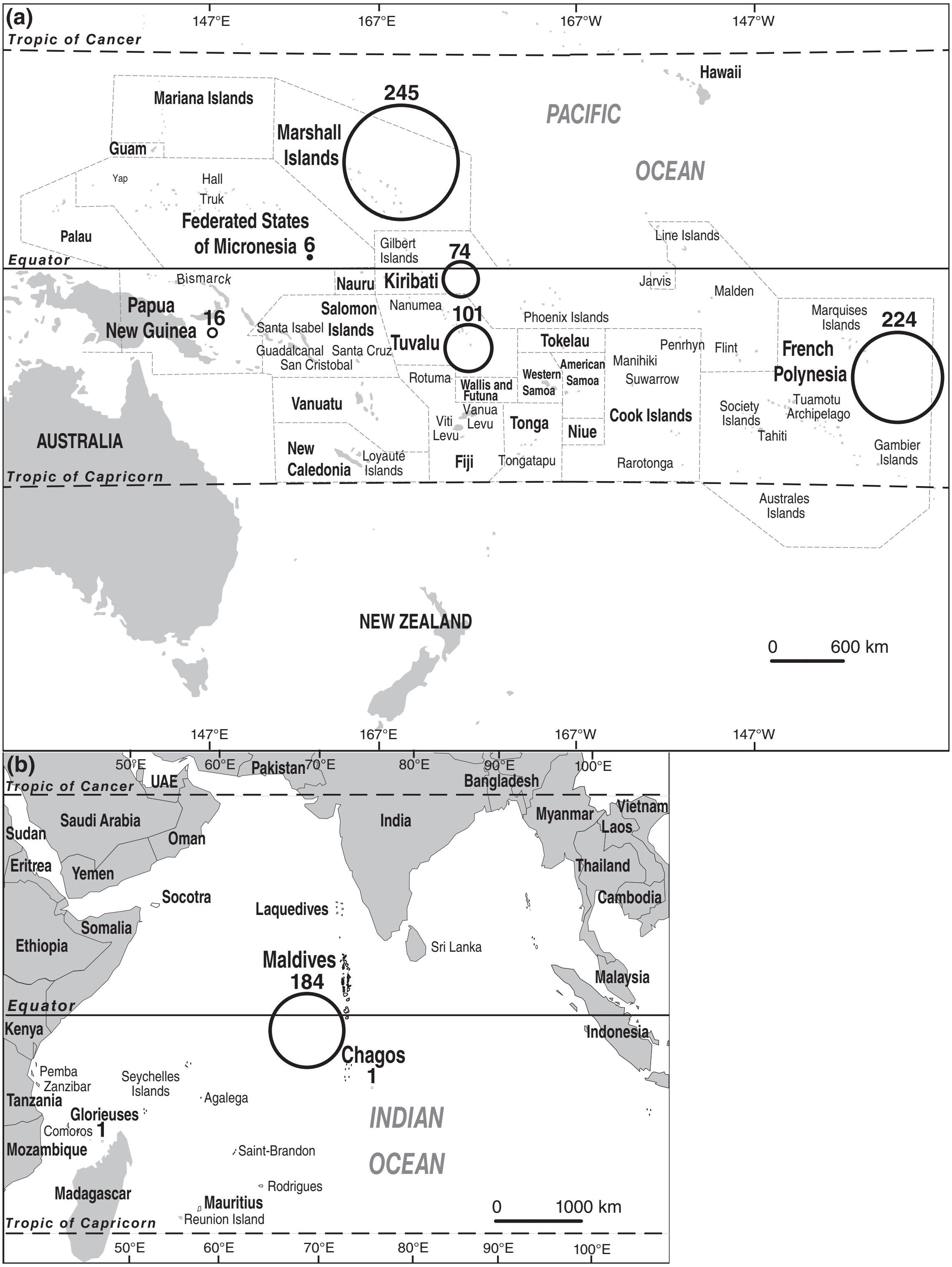

FIGURE 1 Spatial distribution of documented atoll islands (see Table 1 for complementary information)

334 islands larger than 5 ha, which represent 47.10% of the sample islands, showed less contrasting rates of change, that is, ranging from −3% to +10%, except for one island (Anenlibw, Majuro, +19.3%). Second, the direction of change varied with island size. All of the islands larger than 10 ha experienced either stability (209/234 islands, that is, 89.32%) or expansion (25/234 islands, that is, 10.68%). In contrast, islands smaller than 10 ha underwent more contrasting behaviors, as 309 islands out of 475, that is, 65.05%, experienced stability, while, respectively 81 (17.05%) and 85 islands (17.90%) showed contraction and expansion. Importantly, none of the 234 islands larger than 10 ha and only 4 out of the 334 islands larger than 5 ha underwent a reduction in size. The largest islands were the most stable. In the Pacific, where the 16 sample islands larger than 200 ha concentrate, 15 of these islands exhibited areal stability (1 on North Tarawa, 3 in the Marshall Islands, 7 in the

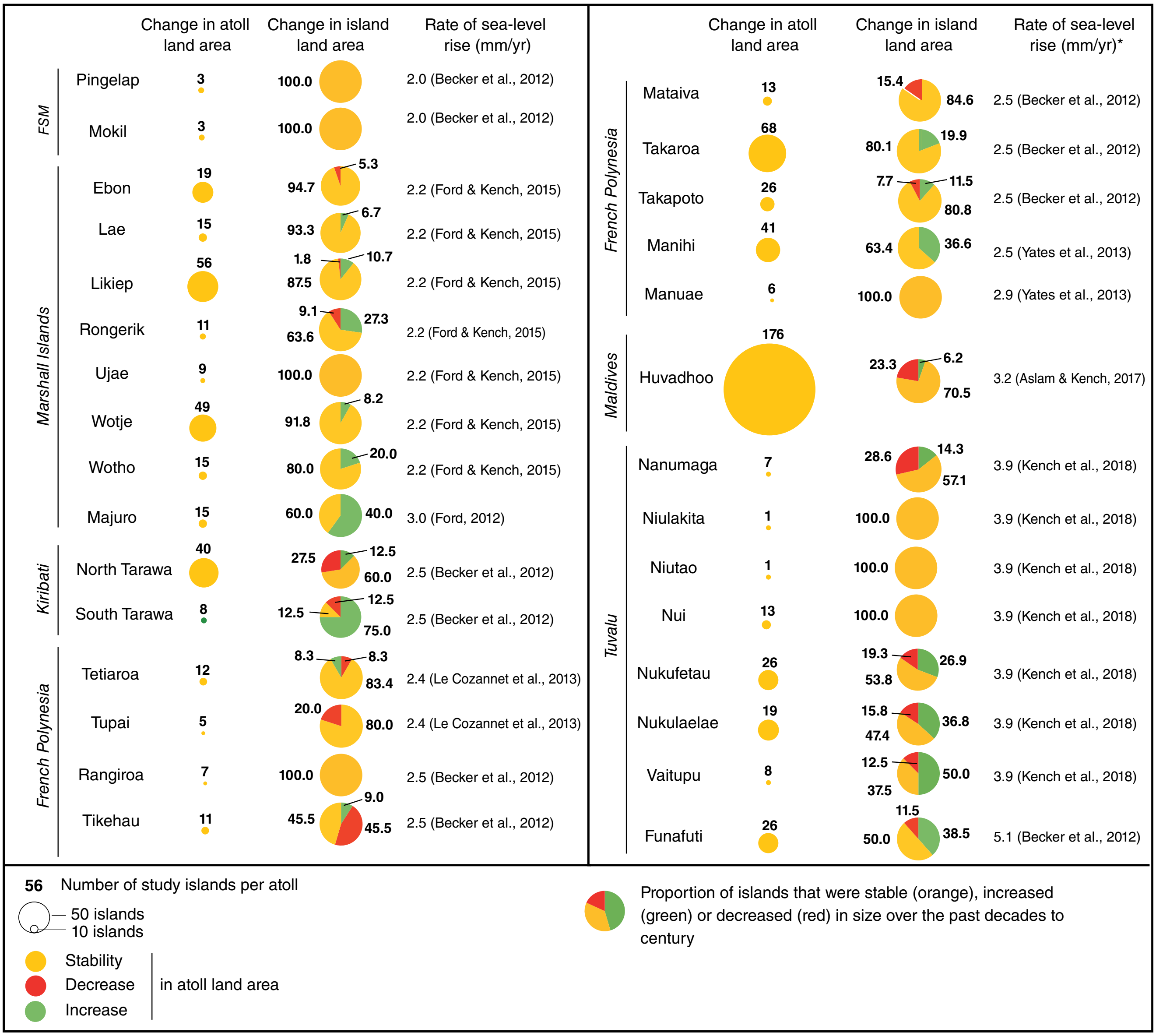

FIGURE 2 Behavior of Pacific and Indian Ocean atolls and islands under sea-level rise (see Table S1 for detailed results). Stability, increase and decrease in land area are defined based on the commonly used ±3% threshold. Island land area was obtained using the vegetation or stability line shoreline proxy (see Table 1 for details). Atoll land area corresponds to the sum of the land areas of the documented islands of a given atoll. Of note, no atoll exhibited a decrease in land area over the past decades to century. Between- and within-atoll island behavior varied significantly, but it shows no relationship with the rate of sea-level rise

Tuamotu, 4 in Tuvalu), with a decadal change in land area < 1%, while the last island (Bonriki, South Tarawa, 863.2 ha) increased in size by 22.6%. Likewise, among the 27 islands having a land area lying between 100 and 200 ha (9 in French Polynesia, 6 in the Marshall Islands, 6 in Kiribati, 5 in Tuvalu and 1 in the Federated States of Micronesia), only 3 increased in area, while 24 were stable.

2.3 | Change in shoreline and island position

2.3.1 | Highly contrasting changes in lagoon and ocean shoreline position

Island shoreline behavior between and within atolls was so variable that no general conclusions can be drawn. In the Pacific, on three atolls, including two Marshallese atolls (Majuro and Wotje) and Manihi (French Polynesia), islands exhibited marked shoreline advance on both ocean and lagoon coasts (Ford, 2012; Ford, 2013; Yates et al., 2013). Over the same period, on four other Marshallese atolls (Ebon, Lae, Wotho, Likiep), the ocean- and lagoon-facing shorelines of islands were predominantly stable and secondarily experienced advance, while on the two remaining Marshallese atolls (Rongerik and Ujae), islands exhibited widespread shoreline retreat (i.e., along 33% of shorelines; Ford & Kench, 2015). Likewise, in the Tuamotu atolls, islands exhibited contrasting shoreline profiles. On Rangiroa and Tikehau, the ocean and lagoon shores of islands alternately

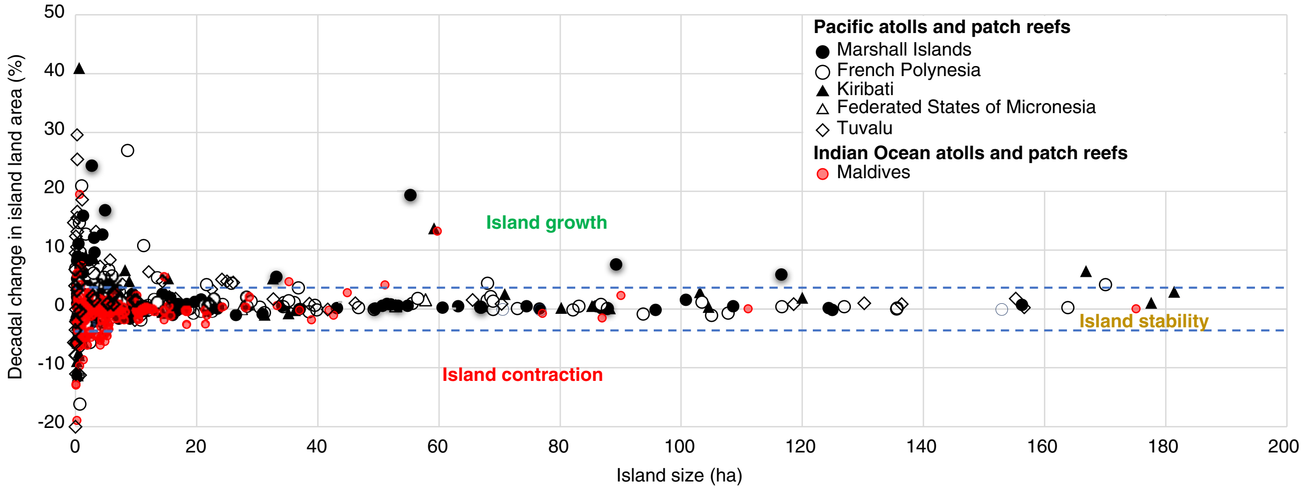

FIGURE 3 Decadal change in island land area for 709 Pacific and Indian Ocean islands. The blue dotted lines correspond to the ±3% threshold. Twenty islands are excluded from this graph, that is, 17 islands >200 ha (7 islands from French Polynesia, 3 from the Republic of the Marshall Islands, 2 from Kiribati, 4 from Tuvalu and 1 from the Maldives) and three islands exhibiting extreme (falling between 125.5% and − 23.2%) values of change (1 from the Republic of the Marshall Islands, 1 from the Maldives and 1 from Tuvalu). The amplitude and direction of change vary with island size. Importantly, none of the islands larger than 10 ha underwent a reduction in size

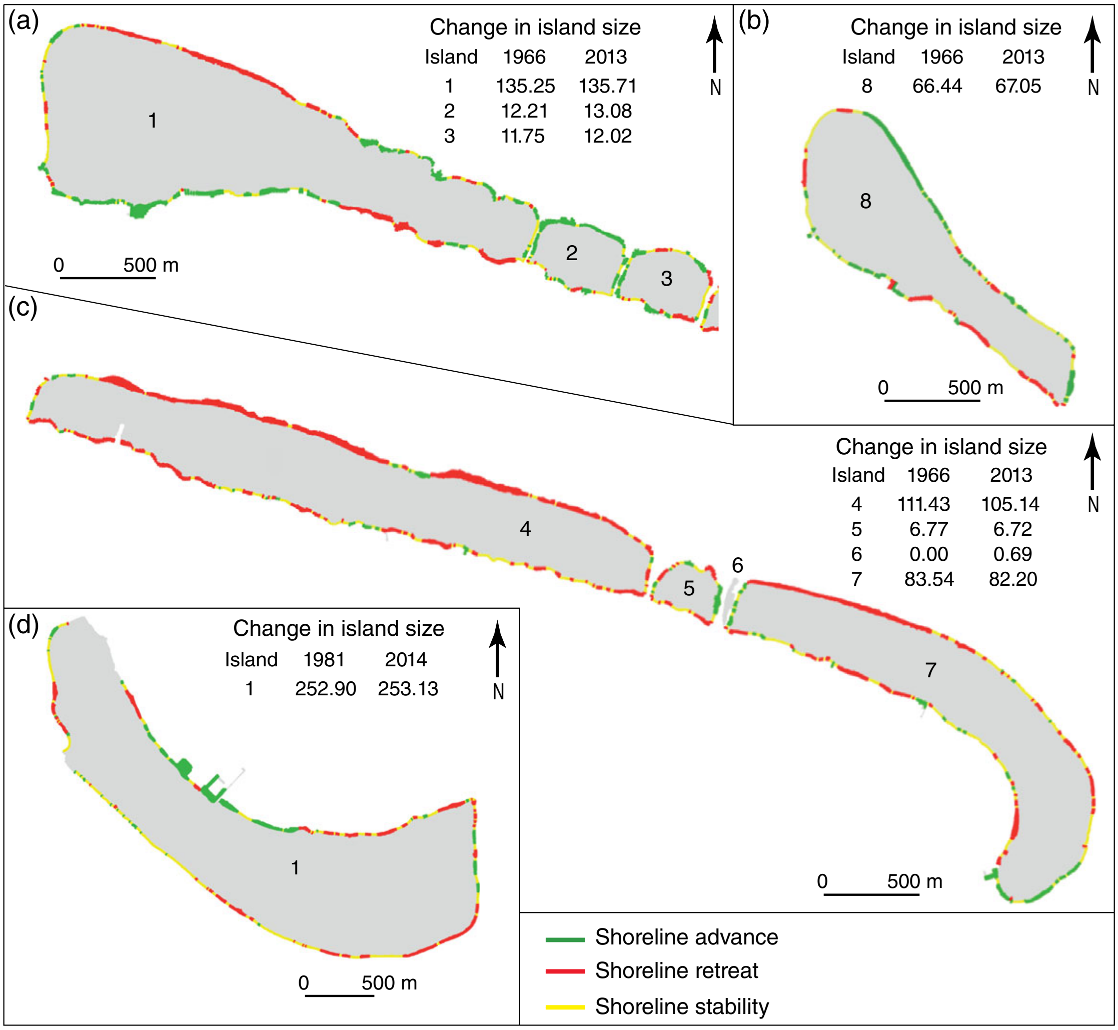

FIGURE 4 Contrasting between- and within-island shoreline changes: Examples of Tuamotu atolls. (a), (b) and (c) show 1966–2013 shoreline (i.e., stability line) changes on the eight most populated and developed islands of Rangiroa, while (d) shows 1962–2014 shoreline changes on the settled island of Tikehau. (a) and (d) illustrate the major role of land reclamation in lagoon shoreline advance. (a) and (c) show hoa infilling, which led to the aggregation of islands Nos 1 and 2. (a) and (c) show examples of large settled islands that exhibited ocean shoreline retreat. Of note, the latter was caused by extensive sediment mining on islands Nos 1 and 4

advanced and retreated over short distances (Figure 4), while on Takapoto, islands experienced contrasting lagoon shoreline behavior and predominantly stable ocean shorelines (Duvat & Pillet, 2017; Duvat, Salvat, et al., 2017). High within-atoll variability between atoll sides and islands was similarly reported in the Society Islands and on Huvadhoo (Aslam & Kench, 2017; Le Cozannet et al., 2013). Of note, where mangroves occur on the lagoon-side of islands (e.g., in Kiribati), they generally expanded seaward, as on Maiana and North Tarawa (Ellison, Mosley, & Helman, 2017; Rankey, 2011). On Maiana, mangrove extension along the shoreline led to a 5% increase in the length of mangrove shoreline. Collectively, these findings confirm high subregional variability in atoll and island behavior.

2.3.2 | Predominance of island positional stability

The great majority of Pacific islands showed positional stability, as illustrated by the Tuamotu atolls, where 85–100% of islands were stable, depending on atolls (Figure 5; Duvat & Pillet, 2017; Duvat, Salvat, et al., 2017). These rates are in agreement with the situation in Funafuti, where for most islands at least 75% of the island footprint has persisted (Kench et al., 2015). However, some islands have migrated over the reef platform, as a result of the differentiated behaviors of their lagoon and ocean shorelines. While some atolls (Pingelap, Mokil, and Taku) showed unidirectional island lagoonward migration, others exhibited opposed windward and leeward situations (Mann & Westphal, 2014; Webb & Kench, 2010). For example, on Funafuti and Takaroa, windward and leeward islands, respectively migrated lagoonward and oceanward (Duvat, Salvat, et al., 2017; Kench et al., 2015). Of note, the smallest islands of Huvadhoo generally exhibited marked positional change, showing either cross-shore migration (either lagoonward, or oceanward), or migration along the reef edge (Aslam & Kench, 2017).

2.4 | Major modes of change in island planform configuration

2.4.1 | Dynamic character of spits, island tips and beaches

Spits, island tips and beaches underwent marked and highly contrasting changes. The changes affecting sand and gravel spits and island tips, which mainly consisted of marked extension or contraction, occurred at the multidecadal timescale. Sand and gravel spits experienced either pronounced longitudinal or lateral extension, or marked contraction, as on Funafuti, Maiana (up to +100 m), Pingelap, Takapoto and most Marshallese atolls, with sand spit extension being the predominant mode of change there (Duvat & Pillet, 2017; Ford & Kench, 2015; Kench et al., 2015; Rankey, 2011; Webb & Kench, 2010). Island tips showed either marked extension or contraction, or pronounced positional change, especially on elongate and on north–south oriented islands (e.g., on Maiana, Aranuka, Mokil, and Huvadhoo), and in hoa-facing areas, for example, on North Tarawa (Aslam & Kench, 2017; Biribo & Woodroffe, 2013; Rankey, 2011; Webb & Kench, 2010). Importantly, beaches experienced substantial changes, not only at the multidecadal timescale, but also over shorter periods of time (i.e., in several years). They underwent either contraction, or rotation (e.g., on Aranuka), with the former leading to beach disappearance on some islands of Taku, Tikehau, and Rangiroa (Duvat, Salvat, et al., 2017; Mann & Westphal, 2014; Rankey, 2011).

2.4.2 | Island aggregation and break up, formation and disappearance, and rotation

The extension of spits and of island tips contributed to island aggregation, which occurred on equatorial and tropical atolls, including Funafuti, Maiana, South Tarawa, Mokil, Rangiroa, Manihi, Palmyra, and most Marshallese atolls (Figure 4a). Island aggregation occurred either as a result of continuous hoa infilling followed by embayment infilling (for example on Funafuti, Maiana, South Tarawa, Mokil, and most Marshallese and Tuamotu atolls (Biribo & Woodroffe, 2013; Ford & Kench, 2015; Kench et al., 2015; Rankey, 2011; Webb & Kench, 2010; Figure 5c)), or as a result of rapid lagoon sedimentation leading to the inclusion of islets and sandbanks on larger islands, as on Palmyra and Diego Garcia (Collen et al., 2009; Purkis et al., 2016). In contrast, island break up into several segments, generally caused by tropical cyclones, was rarely observed, as a limited number of atolls were affected by such events over the past decades. Island formation and disappearance (the latter only affecting very small islets), which occurred at different timescales (from several years to several decades) only occurred on Palmyra, Takaroa, Tikehau, and Nukufetau (Collen et al., 2009; Duvat, Salvat, et al., 2017; Kench et al., 2018; Figure 5a). It is noteworthy that despite widespread island contraction occurring on Huvadhoo, where 23.30% of islands decreased in size, no island disappearance was reported there (Aslam & Kench, 2017). Although rarely noted, island rotation in a constant direction, either clockwise or counter-clockwise, occurred on Pacific (e.g., Tepuka, Funafuti) and Indian (e.g., Grande Glorieuse, French Scattered Islands) Ocean islands (Kench et al., 2015; Testut et al., 2016). For example, Grande Glorieuse underwent a slight rotation in a counter-clockwise direction in only 14 years (1989–2003). On Huvadhoo, some shore parallel islands that expanded over the past four decades also exhibited rotation, although this behavior was rarely noted (Aslam & Kench, 2017). Collectively, these results demonstrate that although atoll islands were highly dynamic over the past decades to century, they rarely underwent major changes in configuration.

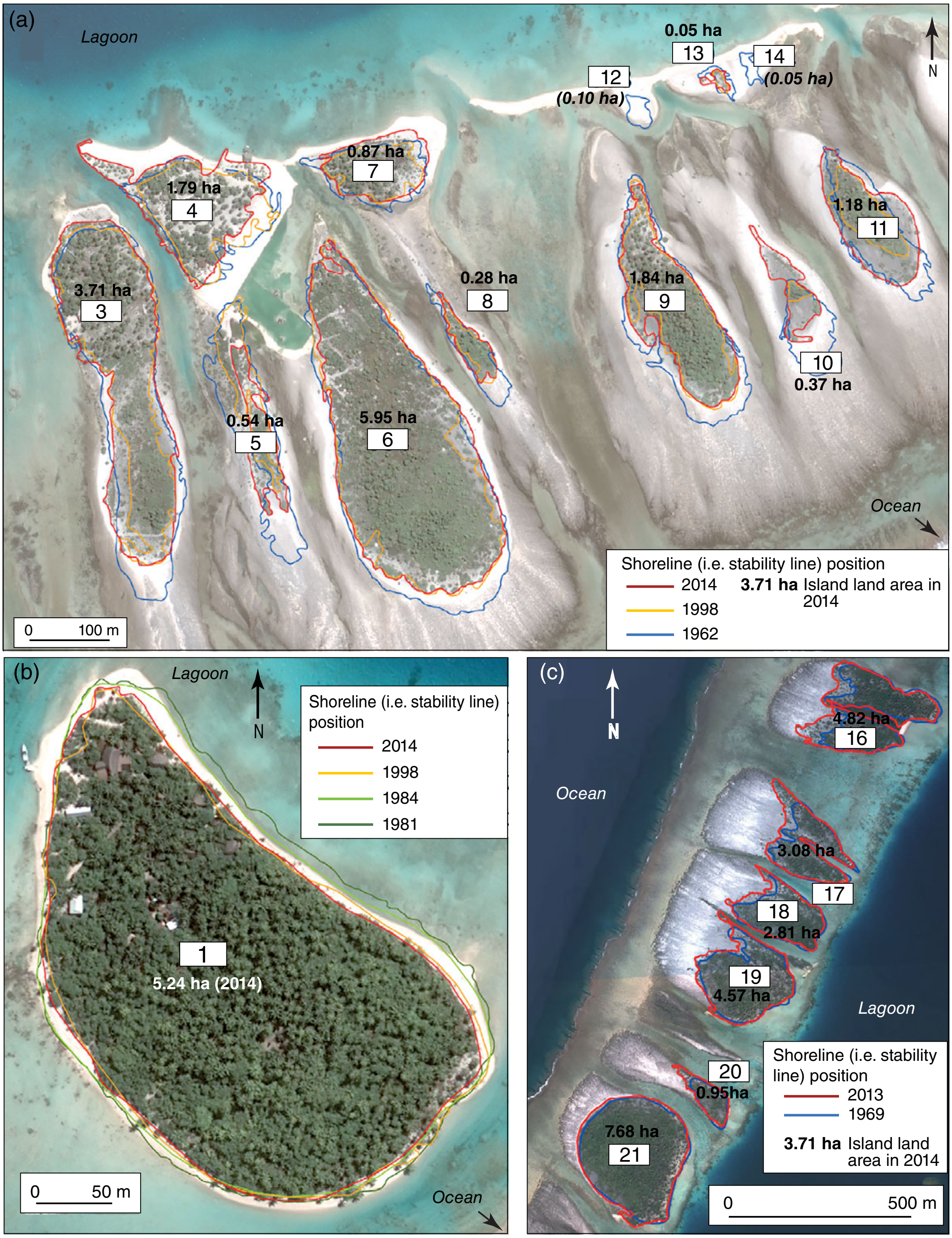

FIGURE 5 Changes affecting islets: Examples of Tuamotu atolls. (a) and (b) show changes affecting some of Tikehau's southern islets, while (c) shows changes affecting Takaroa's western islets. Of note, (a) shows the disappearance of two islets (Nos 12 and 14), and major changes in some islets' configuration and position (Nos 5 and 10). (a) and (b) show that most islets were rather stable in position. (b) Illustrates the retreat of the hoa shorelines of an islet severely affected by the July 1996 distant-source southern swell. (c) Shows significant ocean shoreline advance (islets Nos 16 to 19) and embayment infilling (islets Nos 17 and 19)

3 | ATTRIBUTION OF CHANGE

3.1 | Contribution of climate drivers to regional and subregional variability in atoll and island behavior

Most studies highlighted that although seasonal swell and climate variability were major drivers of recent atoll island planform change, their impacts on islands and shorelines were highly variable (i.e., either accretional, or erosional), due to differences in atoll and island exposure to waves across ocean regions and atoll groups (Andrefouët, Ardhuin, Queffeulou, & Legendre, 2012). For example, the respective contributions of seasonal swell and tropical cyclones were found to vary significantly between French Polynesian atolls. Le Cozannet et al. (2013) noted that changes were predominantly influenced by tropical cyclones on Tupai, while they were mainly controlled by the combined effects of tropical cyclones and trade wind swell on Tetiaroa. Additionally, Yates et al. (2013) and Le Cozannet et al. (2013) found that a given driver, for example, tropical cyclones, had opposite effects on nearby atolls and islands. For example, while the northwest of Manihi exhibited cyclone-induced ocean shoreline accretion resulting from increased sediment transport, the lagoon shore of eastern Manuae and the south-eastern shores of Tupai showed marked cyclone-induced erosion. Likewise, the 1983 tropical cyclones mainly had erosional impacts on the islands of Rangiroa, while they had alternating erosional and accretional effects along the shorelines of Mataiva and Takapoto (Duvat & Pillet, 2017; Duvat, Salvat, et al., 2017). Moreover, major changes in island configuration, such as island aggregation, were caused either by the combined action of tropical cyclones and trade wind swell (e.g., Mataiva; Duvat, Salvat, et al., 2017), or by the predominant action of a given driver (e.g., trade wind swell in equatorial regions). Likewise, spit and island tip extension were driven either by longshore sediment transport attributable to trade wind swell (Collen et al., 2009; Kench et al., 2015; Rankey, 2011; Webb & Kench, 2010), or by massive cyclone-induced sediment inputs (Duvat & Pillet, 2017). Current knowledge on the contribution of distant-source swell to island change confirms that variations in atoll and island exposure to swell are of importance in explaining the high subregional and within-atoll variability observed. While Andrefouët et al. (2012) highlighted the atoll "shadow effect" operating within the Tuamotu chain, Aslam and Kench (2017) hypothesized that the high exposure of Huvadhoo's southern islands to distant-source swell may explain their accretional patterns. However, distant-source swell can also have erosive impacts, as observed on the southern islets of Tikehau following the July 1996 event (Figure 5b). Of note, the smallest islands were found to be the most unstable ones (i.e., marked gain or loss in land area) in the face of climate-related pressures, especially tropical cyclones and distant-source swell. This explains the reduction in size and disappearance of some of the smallest islands (e.g., Tikehau) over the past decades. However, on Huvadhoo, the widespread contraction of islets, which was reported by Aslam and Kench (2017), may be due to sea-level rise-induced sediment reworking. Lastly, the differential influence (e.g., higher in Kiribati compared to French Polynesia) of ENSO across Pacific Ocean subregions likely contributed to variability in atoll and atoll group behavior (Rankey, 2011).

3.2 | Anthropogenic contribution to between- and within-atoll variability

The contribution of human drivers to island planform change was first highlighted in the capital atolls of the Pacific affected by rapid population growth (Duvat, 2013; Duvat, Magnan, et al., 2017; Duvat, Magnan, & Pouget, 2013; Jones & Lea, 2007; Storey & Hunter, 2010; Yamano et al., 2007). Additionally, recent studies emphasized that human activities also caused substantial island and shoreline changes in the settled and also in some unsettled but exploited islands of rural atolls (Aslam & Kench, 2017; Duvat & Pillet, 2017; Duvat, Salvat, et al., 2017; Mann & Westphal, 2014).

In highly modified atoll environments, for example, Palmyra, Majuro, South Tarawa, and some Tuamotu atolls, widespread human-induced degradation of the reef ecosystem was reported, including the alteration of the natural sediment supply by water pollution, and the physical destruction of sand banks, reef flats and shallow lagoon habitats by blasting, dredging and land reclamation (Biribo & Woodroffe, 2013; Collen et al., 2009; Duvat, 2013; Duvat, Magnan, et al., 2017; Duvat, Salvat, et al., 2017; Ford, 2012). This has had detrimental impacts on the capacity of the reef ecosystem to supply islands with sediments and on the physical stability of islands (Duvat, Salvat, et al., 2017; McLean & Kench, 2015). In addition, land reclamation and causeway construction caused major changes in island land area and configuration not only in urban, but also in rural atolls. The former was found to be either a response to land shortage, as on urban Majuro (Ford, 2012) and South Tarawa (Duvat et al., 2013), or a prerequisite for the establishment of an airport or of a military base. For example, on South Tarawa, the infilling of Temaiku Bight undertaken for airstrip construction caused a 363-ha land gain representing 81% of the total 1968–1998 land gain and explaining the profound change in island configuration at the south-eastern angle of the atoll (Biribo & Woodroffe, 2013). Human intervention also caused marked changes in the configuration of Palmyra during the Second World War (Collen et al., 2009). While channel closure isolated some parts of the lagoon, causing changes in sediment transport between lagoon parts, channel opening strengthened lagoon-to-ocean currents, lowering the level of some parts of the lagoon. Here, changes also included the formation of new islands due to the deposition of dredged materials on the reef flat, and a significant increase (+3 m) in artificial island and coast elevation (Collen et al., 2009). Likewise, on Diego Garcia, dredging and reclamation works associated with the establishment of the military base caused an increase in the atoll's land area (Hamylton & East, 2012; Purkis et al., 2016). On Huvadhoo, reclamation works undertaken on 12 islands for urban expansion and harbor construction had the same effect (Aslam & Kench, 2017). Additionally, some studies emphasized that the connection of islands by causeways, by obstructing ocean-to-lagoon sediment transport, changed island and beach configuration and elevation. For example, on Mataiva, causeway construction caused the higher elevation (+0.80 m) of ocean shores compared to lagoon shores (Duvat, Salvat, et al., 2017). Over the past decades, in urban and rural atolls (e.g., Majuro, Tarawa, Taku, Tuamotu atolls), sediment mining from reef flats, ocean and lagoon beaches, and ocean-side sand dunes, carried out by both the public authorities and residents to meet construction needs, contributed not only to beach destabilization, but also to increased wave impact at the coast (Biribo & Woodroffe, 2013; Duvat et al., 2013; Duvat, Salvat, et al., 2017; Ford, 2012; Mann & Westphal, 2014).

Additionally, most studies highlighted the destabilizing effects of shoreline armoring, transversal structures construction and coastal developments on the shorelines of populated (e.g., Majuro, South Tarawa, Taku, Rangiroa) and of unsettled military (Palmyra and Diego Garcia) atolls. Such human interventions were found to disturb sediment transport and deposition, by obstructing sediment transport pathways and by causing the contraction of the accommodation space required for sediment deposition at the coast (Collen et al., 2009; Duvat, 2013; Duvat, Salvat, et al., 2017; Ford, 2012; Mann & Westphal, 2014; McLean & Kench, 2015; Purkis et al., 2016). In some cases, these human disturbances caused the complete destabilization of lagoon shorelines, as on Eita sand spit, South Tarawa, and on Tuherahera island, Tikehau (Duvat, 2013; Duvat et al., 2013; Duvat, Salvat, et al., 2017; Figure 4d). Likewise, on Majuro, Ford (2012) hypothesized that the obstruction of the east-west oriented longshore sediment drift by coastal developments in the Djarrit-Uliga-Delap urban district probably caused a decrease in sediment supply to downdrift rural islands.

Lastly, the widespread removal and the clearing of the native vegetation, respectively caused marked changes in island configuration and shoreline destabilization on some islands, as on Takapoto (Duvat & Pillet, 2017). The degradation of the coastal vegetation even occurred on islands of unoccupied Diego Garcia (Hamylton & East, 2012; Purkis et al., 2016) and of rural North Tarawa (Ellison et al., 2017). These findings confirm the widespread contribution of anthropogenic drivers to island and shoreline change over the past decades to century.

3.3 | Contribution of ecological drivers to regional and subregional variability in atoll and island behavior

The ecological drivers that contribute to island and shoreline change are first, the reef ecosystem, acting as a sediment supplier and as a wave buffer, and second, the native coastal and intertidal (e.g., mangrove forests) vegetation, acting as a sediment trap (Beetham et al., 2017; Duvat, Salvat, et al., 2017; Ellison et al., 2017; Ferrario et al., 2014; McLean & Kench, 2015; Perry & Morgan, 2017).

Island and shoreline change studies have generally interpreted island areal growth as indicating sediment provision to islands by the reef ecosystem (Duvat, Salvat, et al., 2017; McLean & Kench, 2015). Sediment provision to islands may result either from the production of fresh sediments (e.g., due to coral breaking by storm waves), or from the reworking of sediments that had first accumulated on the reef platform. However, due to the absence of data on reef productivity and net carbonate budgets and on reef-to-island sediment transfer for the atolls considered in this review, the contribution of these drivers to between- and within-atoll variations in shoreline and island behavior cannot be determined. Studies conducted in some northern and western Tuamotu atolls, however, highlighted the inhibiting role of the steepness of atoll outer slopes in sediment provision to the ocean shores of islands (Collin, Duvat, Pillet, Salvat, & James, 2018; Duvat, Salvat, et al., 2017; Harmelin-Vivien & Laboute, 1986). In these atolls, the cross-analysis of coral reef data and of island and shoreline response to tropical cyclones showed that despite high reef productivity, the accretional impact of such events was limited by the transfer, and therefore loss, of 75% of broken corals along the outer slopes. The role of atoll bathymetry in recent shoreline change was confirmed by a study on Takapoto Atoll (northern Tuamotu) that showed a strong positive correlation between shoreline erosion versus depth and slope averages, indicating that the deeper and steeper outer slopes are, the more erosional the shoreline was over the past decades (Collin et al., 2018). As variations in reef health (which drives sediment production) and in atoll bathymetry (which drives sediment transfer to the ocean side of islands) can be supposed to be high, these two variables likely contribute to explain variations in island and shoreline change between and within ocean subregions.

Furthermore, as the native intertidal and coastal vegetation contributes to sediment trapping and stabilization, changes in its nature and extent may have contributed to between- and within-atoll and -island variations in shoreline change over the past decades. Given that mangroves are only present on certain lagoon shores (e.g., present in Kiribati, but absent in Tuamotu atolls), their presence or absence may also be a contributory factor for subregional (i.e., between atoll groups) and within-atoll (i.e., between ocean and lagoon shores) variations in island and shoreline behavior.

Importantly, most studies noted that the major controls exerted by climate-related, anthropogenic and ecological drivers on island and shoreline change obscured the detection of the sea-level rise signal.

4 | IMPLICATIONS FOR FUTURE RESEARCH AND ADAPTATION IN CLIMATE CHANGE POLICIES

4.1 | Research gaps

4.1.1 | Addressing geographical gaps

As available studies only cover 35 atolls out of the 439 atolls listed by Goldberg (2016), further studies are required to provide a comprehensive overview of atoll status. Geographical gaps need to be addressed for a better appreciation of regional and subregional variations in atoll island behavior. Future studies should first focus on under-researched regions, that is, the Indian Ocean (3 documented atolls/41) and Caribbean (no data). Second, in the Pacific where the 32 documented atolls only represent 8.35% of the 383 atolls counted by Goldberg, future studies should investigate the numerous and still uncovered atolls of the South China Sea (52 atolls), Indonesia (55 atolls), and Fiji (25 atolls), and provide complementary data on the Papua New Guinea-Vanuatu region (one documented atoll out of 29), the Caroline Islands group (2/34), and French Polynesia (9/78).

4.1.2 | Standardizing methodological protocols and sharing data

Available studies have employed diverse protocols, as illustrated in particular by the use of five different shoreline proxies to assess island areal change (Table 1). This has been useful, as it has emphasized the interest of using a multi-indicator approach to detect not only past-to-present island change (using the vegetation or stability line as a shoreline proxy), but also the presumed erosive impact of accelerated sea-level rise on islands (which may be detected using the base of the beach as a shoreline indicator). However, a standardized methodology is now needed to strengthen the comparability of the data generated, and facilitate the detection of potential regional and subregional variations in atoll, island and shoreline behavior. I therefore recommend that future studies use two complementary indicators, that is, either the vegetation line or the stability line to capture multidecadal island change, and the base of the beach to detect the early impact of sea-level rise on islands. Importantly, the promotion of a standardized methodological protocol also implies that future studies systematically generate the key statistics that allow documenting atoll island change, that is, changes in island area, and in shoreline and island position. Additionally, data sharing within the scientific community involved in atoll studies would provide from now on an updated overview on island change to the advantage of researchers and of atoll countries and territories' decision-makers. The *Atoll Island Database* on which this review relies could serve as a starting point in data sharing.

4.1.3 | Moving from the assessment to the attribution of change

Studies have mainly assessed the risk of island disappearance, therefore providing more limited insights on the drivers of island change. Because most studies were mono-disciplinary (geomorphic), and based on multidate image analysis (without always including fieldwork), ecological and anthropogenic drivers were rarely considered. This is illustrated by the limited number of studies providing a place-specific and in-depth analysis of the contributions of the vegetation and reef ecosystem, and of human activities, to island planform change. The limited accessibility of atolls, high cost of atoll research, and limited local technical and human capacities, also limits in situ data collection. In this context, promoting interdisciplinary research involving in particular geomorphology, numerical modeling of hydrodynamic processes, ecology and human geography, would assist in the attribution of change and in anticipating future changes in the influence and interactions of key drivers.

A better understanding of interactions between the drivers of island change is all the more urgent given that nearshore hydrodynamic processes are expected to change significantly in the future as a result of accelerated sea-level rise (+1.2 to +2 m by the end of the 21st century compared to year 2000 levels; Grinsted, Moore, & Jevrejeva, 2010; Kopp et al., 2014) and increased wave heights (Mentaschi et al., 2017; Shope et al., 2016; Shope et al., 2017). This is especially so if sea-level rise were to outstrip vertical accretion rates of corals (Harris et al., 2018; Perry et al., 2018), as this would increase water depth, and thereby wave heights and wave run-up, over reef flats (Quataert, Storlazzi, van Rooijen, Cheriton, & van Dongeren, 2015; Storlazzi et al., 2018). Such changes in nearshore hydrodynamic processes, which would be exacerbated by a decrease in reef hydrodynamic roughness due to coral decline (Quataert et al., 2015), can be predicted to result in changes in sediment production, transport and deposition, and therefore potentially cause substantial changes to island volume and elevation (Kench & Mann, 2017; Storlazzi et al., 2018). Sea-level rise may cause the re-opening of the “reef energy window” (Kench & Brander, 2006), that is, increase wave energy at island shoreline, which would cause important sediment reorganization through decreased frictional dissipation and increased wave overtopping, especially during extreme events (Kench & Mann, 2017; Quataert et al., 2015; Storlazzi et al., 2018). For example, the 2004 Sumatran tsunami and the 2008 distant-source storm waves, which respectively affected Maalhosmadulu Atoll in the Maldives and Takuu Atoll in Papua New Guinea, caused washover sedimentation that contributed to vertical island building (Kench, Nichol, Smithers, McLean, & Brander, 2008; Smithers & Hoeke, 2014).

4.2 | Implications for risk reduction and adaptation in climate change policies

Tuvalu is the only atoll country for which a complete assessment of areal change has been conducted (in this case showing land area stability; Kench et al., 2018). Consequently, no final conclusion on change in land area can be drawn for other atoll countries and territories. However, as none of the 30 study atolls has decreased in area over the past decades to century, we can hypothesize that these territories have probably also undergone areal stability. This implies that the patterns of population distribution and of inner (i.e., between-atoll) migration in these territories are not at the point of being affected by climate change, which supports the conclusions of Connell (2012), who emphasized the predominant controls exerted by extreme natural events and socioeconomic factors on within-Pacific migrations.

Importantly, the reanalysis of available data on atoll island planform change indicates that over the past decades to century, no island larger than 10 ha and only 4 out of the 334 islands larger than 5 ha (i.e., 1.2%) underwent a reduction in size. Additionally, these islands experienced limited changes in land area (from +3% to +10%). From a geomorphic perspective, we can therefore consider the 10-ha threshold as relevant to define atoll island areal stability. Although this threshold does not consider potential changes in island volume and elevation that would, in the case of a decrease, indicate sediment loss by islands, it should be considered in island development projects, which still target very small (<5 ha) unstable islands, for example, in the Maldives (Aslam & Kench, 2017). Furthermore, this threshold could serve for assessing atoll and atoll countries and territories' vulnerability under climate change. Atolls and atoll countries and territories that are mainly composed of very small islands (e.g., Huvadhoo, and potentially the Maldives as a whole) are undoubtedly more vulnerable to climate change than the ones having larger islands (e.g., Mataiva or Takapoto, that is, French Polynesia).

Due to the highly dynamic nature of atoll islands, adequate settlement and development practices that do not disrupt sediment transport and deposition are required for keeping islands exploitable under sea-level rise over the next decades. In particular, highly unstable areas (e.g., spits, island tips, along-shoreline areas), should not be settled. Given first, the major and increasing contribution of anthropogenic activities to island and shoreline change, and second, the destabilizing effects that they have already had on some islands that have lost the capacity to naturally adjust to climate pressures, limiting human disturbances appears as a priority for adapting to climate change in these territories.

5 | CONCLUSION

This review first confirms that over the past decades to century, atoll islands exhibited no widespread sign of physical destabilization by sea-level rise. The global sample considered in this paper, which includes 30 atolls and 709 islands, reveals that atolls did not lose land area, and that 73.1% of islands were stable in land area, including most settled islands, while 15.5% of islands increased and 11.4% decreased in size. Atoll and island areal stability can therefore be considered as a global trend. Importantly, islands located in ocean regions affected by rapid sea-level rise showed neither contraction nor marked shoreline retreat, which indicates that they may not be affected yet by the presumably negative, that is, erosive, impact of sea-level rise.

Second, this review reaffirms that atoll island areal change was mainly influenced by island size. While the smallest islands (<5 ha, 52.90% of islands) exhibited contrasting areal changes (i.e., stability, increase, or decrease in size) and highly variable values of areal change (from −22.7 to +125.5%), the islands larger than 5 ha (47.10% of islands) generally experienced areal and positional stability. It is noteworthy that no island larger than 10 ha decreased in size, making this value a relevant threshold to define atoll island areal stability. We therefore propose to use this threshold, first, to define the minimum island size required for human occupancy or exploitation, and second, to assess atoll and atoll countries and territories' vulnerability to climate change. Using this threshold for future island development (e.g., resort island) would considerably limit the risk for new developments to be negatively affected by island areal and positional instability, on condition of also avoiding any human intervention that may alter island sediment budget (e.g., sediment extraction) and natural dynamics (e.g., obstruction of sediment transport and deposition by constructions). In addition, the physical instability of small islands (<10 ha) suggests that atoll countries and territories' vulnerability to sea-level rise is inversely proportional to the size of the islands composing them. This for example means that the Republic of Maldives (mainly composed of small islands) is, from a geomorphic perspective, more vulnerable to climate change than the French Tuamotu Archipelago (made up of larger islands). Assessing atolls' and atoll countries' vulnerability to climate change using this threshold would offer a first comprehensive overview of atoll status and of atoll countries' needs in terms of adaptation to climate change. Because they are the most vulnerable, atolls (at the national scale) and atoll countries (at the global scale) having small islands should be the focus of monitoring and assessment activities, and of adaptation efforts.

Third, this paper confirms the highly dynamic nature of some specific atoll island features, such as sand and gravel spits, island extremities, beaches, hoa shores, and ancient hoa areas, which exhibited marked areal and positional changes over the past decades. These changes occurred over short (i.e., several years) to multidecadal timescales, depending on the climate drivers involved (e.g., short term ENSO-influenced beach changes vs. multidecadal shoreline smoothing and spit extension). The highly dynamic nature of these features indicates the continuous adjustment of island shores to climatic conditions, which in turn implies that it is imperative to limit as much as possible human interventions that may destabilize the fragile equilibrium of such islands. This once again emphasizes the crucial need for a better consideration of island dynamics in development projects.

Fourth, this paper shows that over the past decades, atoll islands exhibited highly contrasting behaviors across ocean basins and subregions. No distinct regional (i.e., scale of ocean basins or ocean subregions) or subregional (i.e., scale of atoll groups) profiles emerge from this global review. In some cases, nearby atolls exhibited contrasting behaviors, for example, a majority of expanding vs. a majority of contracting islands, or opposite behaviors of their leeward and/or windward sides. Likewise, within a given atoll, nearby islands and island shorelines (either ocean-facing, or lagoon-facing) commonly experienced opposite behaviors. The patterns of atoll island planform change are resolutely atoll- and even in some cases island-specific. This conclusion suggests that the atoll and island "shadow effects" (Andrefouët et al., 2012), which contribute to the contrasting responses of nearby atolls and islands to rather similar climatic conditions, play a major role in explaining the contrasting behaviors of atolls, atoll sides, islands and island shorelines, within a given atoll group.

Further research should address four priorities: (a) fill geographical gaps by focusing on Indian Ocean, Caribbean and north-western Pacific atolls; (b) use a common assessment protocol to strengthen data comparability; (c) further investigate ecological drivers to be able to determine changes in reef productivity; (d) promote interdisciplinary approaches, especially nearshore processes modeling, to better capture potential changes in drivers' interactions that may alter the fragile equilibrium of atoll islands.

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CONFLICT OF INTEREST

The author has declared no conflicts of interest for this article.

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SUPPORTING INFORMATION

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