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Key Points:

- Within decades, atolls will experience accelerating instability, loss of potable groundwater and agroforests, and threatened infrastructure
- Atoll islands will become permanently unstable (with no action) prior to 2100 as future sea level exceeds late Holocene threshold values
- Adaptation measures that incorporate natural and engineered forms of resiliency and atoll community values need to be implemented now

Supporting Information:

- Supporting Information S1

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Rethinking Reef Island Stability in Relation to Anthropogenic Sea Level Rise

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Abstract Unprecedented rates of anthropogenic sea level rise (ASLR) and attendant wave-driven flooding and salinization threaten the stability (and habitability) of atoll islands. Thus, there is doubt regarding the continued existence of sovereign atoll nations and unique, place-based indigenous atoll cultures. Evidence that some atoll islands may have originally formed in the latter stages of post-glacial sea level rise (SLR) has been interpreted to mean they will persist under accelerating ASLR. These forecasts are at odds with interpretations that atoll islands will succumb to rising seas. To shed light on conflicting models of island stability, we develop a multitemporal island vulnerability assessment (MIVA) to anticipate island instability and apply it in the Republic of the Marshall Islands (RMI) where there is a history of previous research. Using evidence from geological and historical records of island response to changing late Holocene sea level and modern tide, wave, and groundwater observations, we identify thresholds where islands pass from stable to unstable phases due to projected local, relative ASLR. Under the most likely scenario (intermediate-high) where ASLR reaches 1.91 m by 2100, island stability deteriorates by midcentury as historical rates of SLR at RMI increase threefold, and temporary flood events deteriorate potable groundwater and agroforests. In the second half of the century, as ASLR exceeds geological sea level thresholds, permanent island instability will be inevitable with no action. We conclude that these islands are already trending into declining stability due to ASLR as documented by published observations of extreme tides, wave inundation, salinization, and sediment mobilization.

Plain Language Summary Atoll islands are low-elevation accumulations of sand and gravel with thin aquifers and productive agroforests. Researchers disagree on whether atoll islands will be stable and habitable as sea level rises. We designed a method that integrates fossil data recording the origin and evolution of these islands, changes in island size from historical photographs, and modern observations of impacts from extreme tide and wave events, to define thresholds and time frames where islands transition from stable to unstable. We consider a range of future sea level rise scenarios and find that in all cases, islands experience rapid decreases in stability by midcentury. In the most likely scenario, the rate of sea level rise will triple and groundwater sources will be permanently lost, within only a few decades. Under an extreme scenario, islands will be fully unstable, the rate of sea level rise will triple, and community infrastructure will be at intolerable levels of risk as regional sea level exceeds 1 m by the year 2060. We urge that adaptation strategies be implemented now, that they incorporate both natural and engineered forms of resiliency, and that they be grounded on the principle that resilient islands also sustain the cultural identity of island people.

1. Introduction

Low-lying (1–3 m) reef islands composed of an unconsolidated sand and coral rubble base (Woodroffe, 2008) and thin, rain-fed freshwater aquifers and productive agroforests (MacFarland et al., 2017) provide the only habitable land for atoll communities. High-end anthropogenic sea level rise (ASLR) projections (~2 m) (Bamber et al., 2019) exceed the average elevation of these low islands and threaten the sustainability of fundamental resources (e.g., fresh groundwater, soil) within the lifetime of current residents. Despite many accounts of atoll island vulnerability (Dickinson, 2009; Quataert et al., 2015; Storlazzi et al., 2015), some geological and historical records have been interpreted to suggest that atoll islands are resilient to ASLR (Kench et al., 2015, 2018; Webb & Kench, 2010).

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The future of atoll islands is tied to ASLR, a function of marine thermal expansion (Cheng et al., 2019) and global mass loss from the cryosphere (Sheperd et al., 2018). Studies reveal increasingly dire trends in these drivers. Mountain glaciers are in a state of decay and the rate of loss (335 billion tons of ice per year) has accelerated over the last 30 years (Zemp et al., 2019). Ice loss on Greenland is seven times faster than it was in the 1990s (Sheperd et al., 2020) and has doubled since a decade ago (Mouginot et al., 2019). A record 600 billion tons of ice melted on Greenland in 2019, enough to raise global sea level by 2.2 mm in just 2 months (Velicogna et al., 2020). Snowfall that normally replenishes Greenland's glaciers each year can no longer keep up with the pace of ice melt, and researchers have concluded that Greenland's melting ice sheet has passed the point of "no return" (King et al., 2020). Mass loss from both Greenland (Trusel et al., 2018) and West Antarctic (Lenton et al., 2019) ice sheets is approaching or has already exceeded a "tipping point" beyond which melting becomes unstoppable.

Furthermore, targets to stop fossil fuel emissions before reaching dangerous levels of warming are being missed (SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP, 2019). The drivers of ASLR are increasingly likely to grow due to inputs from committed warming due to past emissions (Mauritsen & Pincus, 2017), rapidly narrowing carbon budgets to stop warming at 1.5°C (IPCC, 2018), socioeconomic inertia related to existing fossil fuel infrastructure (Tong et al., 2019), accelerated rates of warming (Xu et al., 2018), and projections of continued greenhouse gas emissions over the next few decades (Newell et al., 2019).

In 2019 (Oppenheimer et al., 2019), the Intergovernmental Panel on Climate Change (IPCC) published the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Related to ASLR, the SROCC found that (1) the dominant cause of sea level rise (SLR) since 1970 is anthropogenic forcing and in the future will be strongly dependent on greenhouse gas emissions; (2) relative to 1986–2000, sea level is projected to rise by 0.29–1.10 m by 2100; and (3) beyond 2100, ASLR will continue for centuries due to continuing deep ocean heat uptake and mass loss of the Greenland and Antarctic ice sheets and will remain elevated for thousands of years.

Emerging science suggests that IPCC projections may understate the probability of faster-than-expected ice sheet melt, particularly for high-end warming scenarios. Physical feedback mechanisms that may lead to rapid ice sheet collapse include marine ice sheet instability, ice cliff instability, ice shelf hydrofracturing (Pattyn & Morlighem, 2020), ice dynamics at the base of outlet glaciers (Mouginot et al., 2019), and on Greenland, reductions in surface albedo (Ryan et al., 2019) and cloud cover (Hofer et al., 2017). Self-amplifying feedbacks, especially in the Antarctic ice sheet, may add between 0.2 to 1.1 m to estimates of current century ASLR under intermediate and higher warming scenarios (Pollard et al., 2015). Global climate models such as those used by the IPCC lack the capacity to project these rapid changes in ice sheets that might be triggered by warming conditions. The IPCC projections of future ASLR can be seen as overly conservative given the above discussion of increasingly unstable behavior of Greenland and West Antarctic ice sheets, projections of continued emissions, and signs that avoiding unsafe levels of warming are increasingly unlikely (Jackson et al., 2019; Peters et al., 2020). This is consistent with the recent findings of a structured expert survey that found a 1 in 20 chance (5%) that seas could rise by more than 2 m by 2100 (Bamber et al., 2019).

Faced with considerable uncertainty, atoll communities need guidance in planning for growing risk associated with future ASLR. Sweet et al. (2017) published six physically plausible ASLR scenarios based upon peer-reviewed research observations. The two lowest scenarios are exceeded by the current rate of global SLR (Nerem et al., 2018), rendering them void. The remaining four global scenarios are translated to regional ASLR estimates by combining climate-related processes (thermal expansion, ice sheet mass loss) with global gravitational and glacioisostatic processes that influence ASLR.

Published assessments of ASLR impacts upon atoll islands present conflicting interpretations of island stability. We find that these studies are based on interpretations of data from three different time scales: (1) the geologic record, (2) the historical record, and (3) modern observations and modeling. Below, we review these approaches, propose a unifying model that integrates the three time scales, and apply it to develop projections of island stability in the Republic of the Marshall Islands (RMI) under scenarios of ASLR as defined in Table 1.

2. A Temporal Review of ASLR Impacts Upon Atoll Islands

2.1. Geologic Record

Studies that implement data from the geologic record show that reef islands that form upon atoll and open ocean reef platforms are among the youngest geological formations in the world (typically less than

Table 1
ASLR Specific to Majuro Tide Gauge, Combined Geophysical and Climate Processes (Sweet et al., 2017)

Scenario	Intermediate	Intermediate-high	High	Extreme
SLR, RMI (2100)	1.2 m	1.91 m	2.64 m	3.23 m

5,500 cal year BP) (Kench et al., 2005). Reef island formation is dependent upon sea level change, reef growth, and island sediment availability (Perry et al., 2011; Woodroffe, 2008). Following the last ice age, sea level in the equatorial Pacific stood 1–2 m higher than present as recently as 2,000–5,000 years ago (Dickinson, 2009; Fletcher & Jones, 1996; Grossman et al., 1998).

Using data from the geologic record, research seeking to identify the timing and chronology of reef island formation is inconsistent. Studies propose that islands formed in the latter stages of post-glacial SLR (Kench et al., 2005, 2014), during the highstand (Kayanne et al., 2011), and as sea level fell in the recent 1,000–2,000 years (post-highstand) (Mckoy et al., 2010; Woodroffe & Morrison, 2001). Geologic studies argue that island resiliency is directly related to the timing of island formation, such that those islands that formed during mid-Holocene SLR may be more resilient to future SLR (Kench et al., 2005) because these islands are composed of sediment sources adapted to higher water levels and increased hydrodynamic energy (Perry et al., 2011).

2.2. Historical Record

Studies centered upon the historical record couple local rates of ASLR, with a limited number (1–3) of available aerial images from the last century to characterize changes in island area and shoreline position relative to changes in sea level (e.g., Duvat, 2018). Analyses of historical aerial imagery have led workers to conclude that the majority of atoll islands (88.6%) in the Pacific and Indian Oceans (Duvat, 2018) have remained stable or increased in area (e.g., Tuvalu, Kench et al., 2018; Webb & Kench, 2010; the RMI, Ford & Kench, 2015; French Polynesia, Duvat & Pillet, 2017; Federated States of Micronesia; and Kiribati, Webb & Kench, 2010). Historical imagery analyses also document the impacts of anthropogenic drivers upon the stability of urban islands. Increases in urban island area have been attributed to reclamation and development onto the reef flat, while disjointed reclamations and coastal structures that interrupt longshore sediment transport have been attributed to pockets of shoreline erosion (Biribo & Woodroffe, 2013; Ford, 2012). Furthermore atoll island stability has been correlated with island size, such that larger islands ($>0.1 \text{ km}^2$) are typically more stable than atoll countries composed of small islands ($<0.1 \text{ km}^2$) (Duvat, 2018).

Researchers have concluded from historical imagery that island persistence and even growth are widespread despite local relative SLR ranging from 2.0 ± 0.6 (Pingelap, Mokil) to 5.1 ± 0.7 (Funafuti, Tuvalu) mm/year (Becker et al., 2012; Duvat, 2018). On the basis of these measurements, it is argued that islands will continue to persist as physical sites for human habitation over the next century (Kench et al., 2018) assuming that local ASLR rates do not drastically accelerate.

2.3. Modern Observations and Modeling

Modern observations document nearly a decade of wave overwash and flooding related to extreme wave events (Becker et al., 2014; Merrifield et al., 2014; Quataert et al., 2015; Storlazzi et al., 2015). Future projections suggest that ASLR will enable larger wave runup at shorelines from extreme events (Storlazzi et al., 2011). Furthermore, with continued ASLR, more frequent flooding and overwash may result from smaller offshore wave heights (Cheriton et al., 2016).

Physical modeling studies have identified that under elevated ASLR (0.5–1.0 m), overtopping and overwash will enable islands to vertically accrete at rates that track future ASLR (Tuck et al., 2019). However, modeled wave washover at 1 m of ASLR is accompanied by whole island rollover processes and subsequent island migration across the reef surface (Kench et al., 2018; Tuck et al., 2019). Furthermore, narrow islands located on narrow ($<500 \text{ m}$) and deep ($>1 \text{ m}$) reef flats are typically more susceptible to remobilization of island sediment with ASLR (Shope & Storlazzi, 2019). While these processes may ensure that sparsely populated islands remain on reef platform surfaces under moderate sea level conditions, wave-driven flooding and island migration due to wave overwash and overtopping processes will quickly impact island habitability.

Field observations document that aquifer salinization resulting from wave overwash required nearly 2 years for recovery (Gingerich et al., 2017). Modeling by Storlazzi et al. (2018) found that by midcentury, a growing frequency of wave overwash and salinization associated with ASLR increasingly threatens aquifer recovery

and, by extension, island habitability. For atolls relying on alternative potable water (e.g., catchment and desalinization facilities), Storlazzi et al. (2018) found that annual flooding by the end of the century places intolerable risk on infrastructure and daily lifestyle.

3. Materials and Methods

Collectively, the conflicting conclusions of ASLR impacts make it difficult to design adaptive management strategies. Here we present an alternative examination of the vulnerability and resiliency associated with ASLR using data from the RMI. We integrate data spanning all three time scales, a method we refer to as multitemporal island vulnerability assessment (MIVA).

The RMI has one of the richest data sets spanning the three time periods. The nation is composed of 29 atolls and 5 mid-ocean reef platform islands aligned along two nearly parallel chains between 4°34' to 14°43'N and 160°48' to 172°10'E (Figure S1). Island sediment is derived entirely from the nearshore coral reef ecosystem and deposited upon carbonate platforms (i.e., fossil reefs) located within atoll lagoons, atoll rims, or mid-ocean reefs.

The region is characterized by light northeasterly tradewinds (6.32 m/s) and tradewind swell, which predominate for most of the year. Larger swells with heights generally <2.3 m occur in the winter and spring months (Bosserele et al., 2015). Typically, the largest wave overwash events coincide with extreme tides (highest tides of the year) and have caused inundation, coastal erosion, and protracted salinization of freshwater aquifers (Storlazzi et al., 2018), soils, and community infrastructure.

3.1. Geological Record: Modeling Impacts of Middle to Late Holocene Sea Level Change on Atoll Island Formation

Here we present a detailed chronostratigraphic study of the RMI. Atoll island formation is examined in relation to reef flat development, middle to late Holocene sea level change, hydrodynamic energy, and sediment production and delivery. Moving past individual characterizations of islands, we propose overarching principles that capture the depositional history among reef islands within a single atoll and between atoll and reef platform islands.

Geologic data collected in this study at Bokollap Island (windward Majuro) are supplemented with previously published radiocarbon dates and stratigraphic descriptions from Laura Island (leeward Majuro) (Kayanne et al., 2011) and Jabat Island (Kench et al., 2014), a mid-ocean reef platform located approximately 230 km WNW of Majuro Atoll (Figure S1).

Topographic surveys of reef islands were undertaken at windward Majuro using a Leica TC407 total station, at leeward Majuro using an auto level (AE-5, Nikon Corp., Japan) or a total station (GTS-320, TOPCON Corp., Japan) and at Jabat Island using a laser level and RTK GPS. All surveyed elevations were tied to local mean sea level (MSL) with reference to the MAJURO-C (<http://www.iocsealevelmonitoring.org/station.php?code=marsh>) or Kwajalein (<https://tidesandcurrents.noaa.gov/stationhome.html?id=1820000>) tide stations.

Elevations at windward Majuro were further corrected using a temporary tide gauge installed in the lagoon. Surveyed points were adjusted to geographic coordinates and ellipsoid heights relative to the World Geodetic System 1984. Surveyed data points at windward Majuro have a horizontal accuracy of ± 1.0 m and a vertical accuracy of ± 0.03 m. The accuracy of topographic data at Jabat Island and leeward Majuro sites was not reported (Kayanne et al., 2011; Kench et al., 2014).

To determine origin and direction of sediment transport at windward Majuro, we conducted a compositional analysis on a minimum of 200 identifiable grains from samples derived from the reef flat, modern beach, and island stratigraphy as revealed in six trenches excavated to expose depositional history. Dominant biogenic components included foraminifera (*Calcarina*, *Amphistegina*, *Sortidae*, and others), coral, coralline algae, *Halimeda*, mollusk, and echinoderm fragments. A spine ratio metric was calculated to account for the abrasion of *Calcarina* tests and track the predominant direction of sediment transport. Following Yasukochi et al. (2014), spine ratios were calculated (Equation 1) as follows:

$$\text{spine ratio (\%)} = 100 \times (A + B) / (A + B + C) \quad (1)$$

Grade A had complete spines, grade B had some spines, and grade C had no spines (Yasukochi et al., 2014). Only those *Calcarina* that retained their spines (A or B) were submitted for radiocarbon dating because these samples have the shortest lag times between removal from the reef flat and incorporation into island sediments.

Here we leverage a three-phase island building model (Yasukochi et al., 2014) that links Pacific reef island formation with middle to late Holocene sea level change (Figure 1, discussed below). Radiocarbon ages were measured by accelerator mass spectrometer (AMS). Island formation was determined from *Calcarina* foraminifera bulk samples collected at Majuro, while at Jabat, both *Calcarina* and coral-algal sand samples were dated. Handheld gas-powered drills attached to diamond core bits were used to extract 1–2 m long cores from the reef flat adjacent to each island. The timing of reef flat progradation was determined from in situ corals in geologic cores.

To provide consistency among all three study sites, radiocarbon ages from distinct reef cores and island sediments were recalibrated for the regional marine reservoir effect using CALIB version 7.1 and Marine13 calibration data set (Reimer et al., 2013; Stuiver & Braziunas, 1993) (<http://calib.org/calib/calib.html>) (Table S2). The local marine reservoir effect for the RMI was estimated from a single $\Delta R = -35 \pm 25$ years, derived from the comparison of melon-headed whale bones and charcoal specimens removed from the same stratigraphic unit at Laura Island, Majuro Atoll (Kayanne et al., 2011).

3.2. Reconstructing Middle to Late Holocene Sea Level Change

The RMI sea level history extending from 5,300 cal year BP to present was reconstructed from previously published (Kayanne et al., 2011; Kench et al., 2014; Tracey & Ladd, 1974) survey grade microatoll data recovered at four islands within the RMI (Table S3). Intertidal corals such as microatolls are believed to be the most precise sea level indicators with an indicative range as low as 3 cm (Smithers & Woodroffe, 2000). Living microatolls are precisely constrained by modern sea level, and as such, the age of fossil microatolls and the height of living microatoll corals (HLC) can be used to infer MSL for specific points in the past.

We updated the Holocene sea level history at Majuro to remove discrepancies among multiple marine reservoir values, the confidence interval of reported ages, and the lack of survey grade elevation values. Thus, each data point used to construct the revised RMI sea level curve (Figure 2a) represents the following: (1) surveyed elevations tied to modern MSL using site-specific HLC and (2) recalibrated radiocarbon ages (2σ) as described previously for RMI.

3.3. Deriving Place-Based Sea Level Thresholds and Time Frames

Local sea level thresholds (Table 1) for mid-Holocene island building at RMI were determined by comparing the geologic record of reef island formation to the middle to late Holocene sea level curve (Figure 2a). Sea level threshold values are defined by the maximum and minimum sea level values that constrained initial island building and stabilization. To determine local time frames of island instability, MIVA intersects minimum and maximum sea level threshold values with projected ASLR estimates and rates given current scientific understanding and assumptions of projected greenhouse emissions. Here we assume that as the magnitude of ASLR exceeds mid-Holocene highstand values ($1.14 + 0.41$ m), islands in the RMI will become unstable as they are permanently exposed to water levels that are higher than those under which they originally formed.

The ASLR scenarios for the RMI developed by Sweet et al. (2017) are scaled specifically to the tide gauge at Majuro and account for ice sheet and glacier mass changes, oceanographic processes, land-water storage, glacial isostatic adjustment, and tectonics and sediment compaction. Here we employ the regional ASLR projections with ± 1 standard deviation (1σ) for Majuro Atoll to provide estimates of the magnitude and rates of ASLR up to the year 2100. Minimum and maximum sea level threshold values are intersected with ASLR projections to estimate time frames of island instability at RMI.

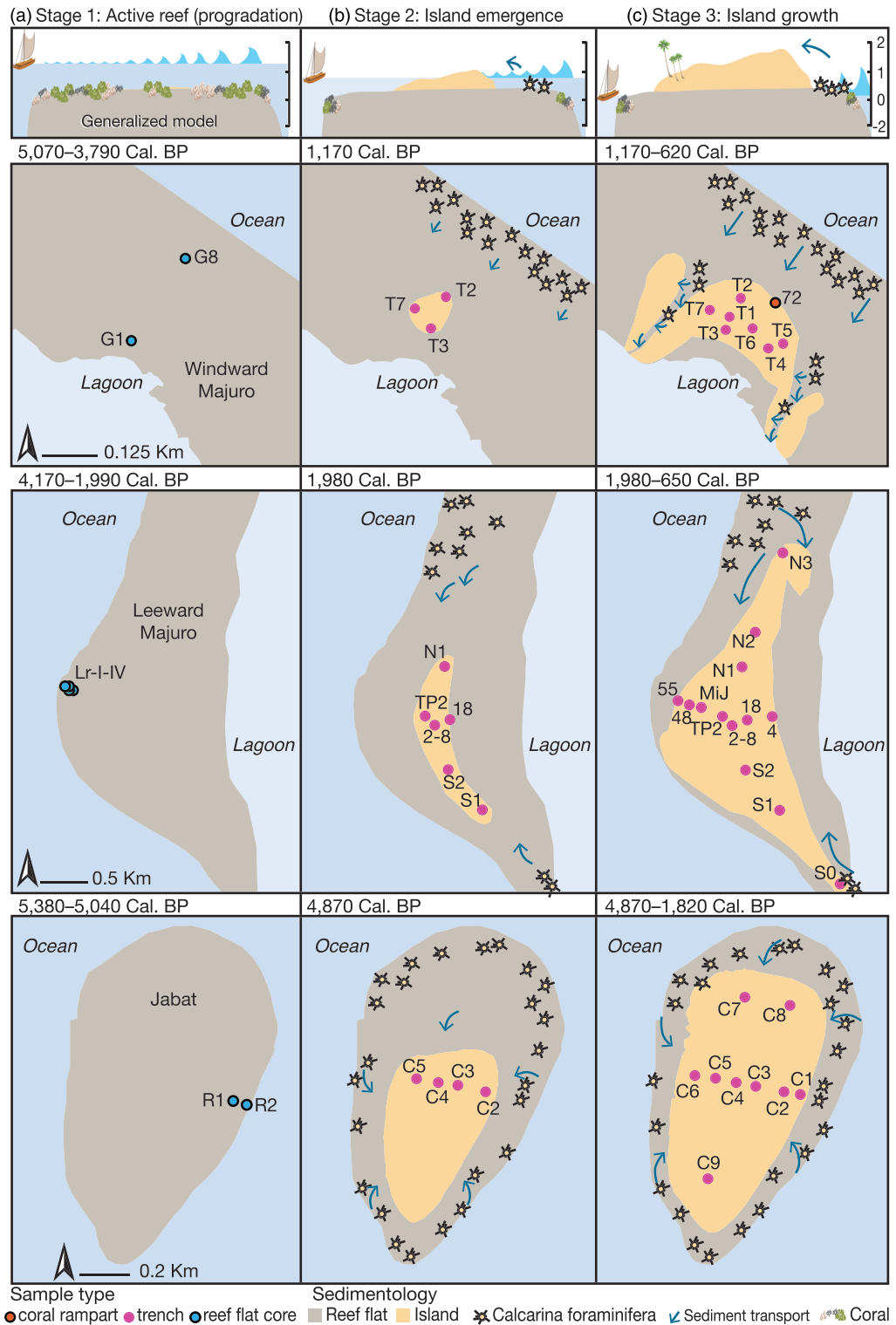


Figure 1. A four-stage, generalized island formation model based on geologic data collected at windward Majuro (this study), leeward Majuro (Yasukochi et al., 2014), and Jabat Island (Kench et al., 2014). (a) Stage 1. Reef flat progradation as sea level rise approached the highstand and the rate of rise slowed, triggering a decrease in the rate of vertical reef accretion. (b) Stage 2. Decreased hydrodynamic energy promoted sediment deposition and triggered island emergence as sediment accumulated on the fossil reef flat. (c) Stage 3. Rapid island building as *Calcarina foraminifera* replaced coral as the dominant sediment producers along the reef flat. (d) Stage 4 (not shown). Reef islands stabilize, island building ceased, and minor episodes of island reconfiguration occur, limited to spits and beaches.

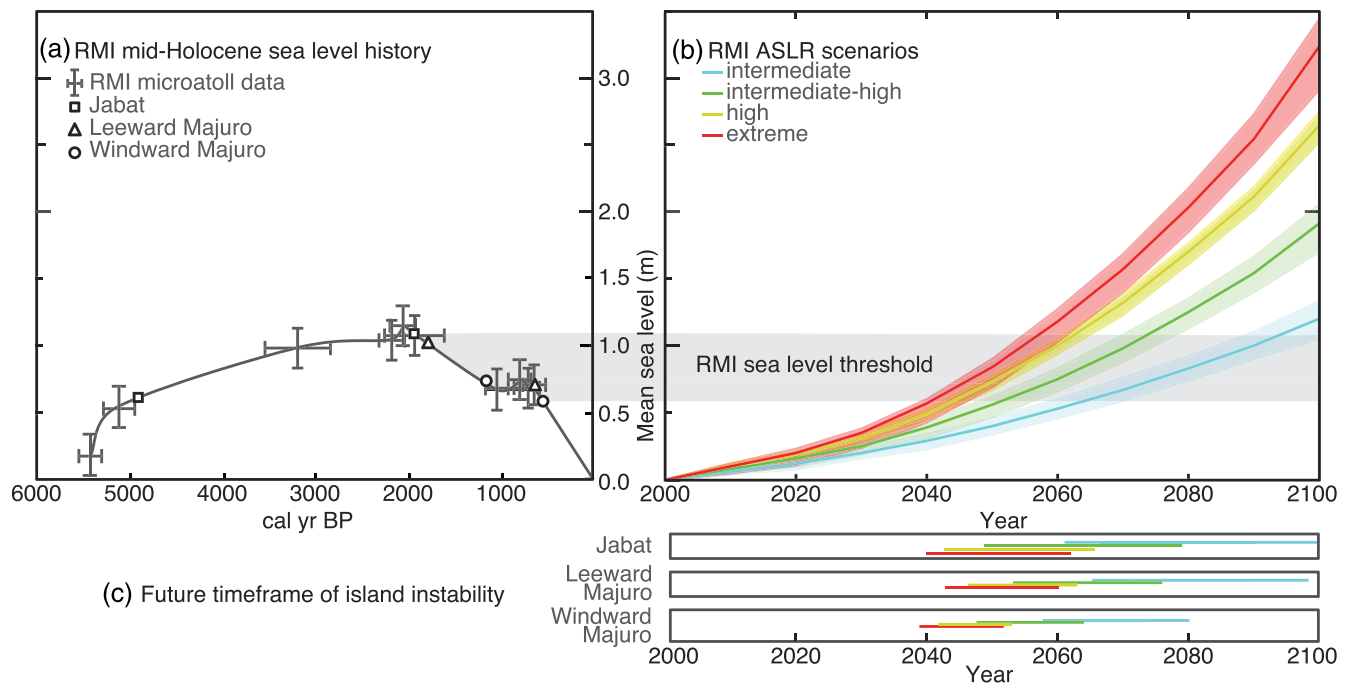


Figure 2. Sea level threshold. (a) Middle to late Holocene sea level history for the Republic of the Marshall Islands (RMI) inferred from previously published (Kayanne et al., 2011; Kench et al., 2014; Tracey & Ladd, 1974) survey grade microatoll data. Error bars define uncertainty in the age (2σ) and elevation of microatolls. Sea level threshold values are determined by comparing the timing of island formation at Jabat Island, leeward Majuro, and windward Majuro to the RMI mid-Holocene sea level curve. (b) Mid-Holocene sea level threshold values are compared to future ASLR projections specific to Majuro tide gauge (Sweet et al., 2017). (c) Local time frames of instability predicted for each island are determined by intersecting island specific threshold sea level values with future ASLR curves.

3.4. Re-Evaluating Time Frames of ASLR Impacts Using the “Historical Record” and “Modern Observations and Modeling”

The MIVA framework enables time frames of island stability derived from “the geologic record” to be refined through comparisons with published data sets from the historical record and modern observations and modeling. The historical record documents changes in shoreline position and island area between 1943 and 2010 at 10 of the 34 atoll and mid-ocean reef platform islands (108 reef islands total) within RMI (Ford, 2012, 2013; Ford & Kench, 2015) (Table S1). Tide gauge records at Station 1820000 Kwajalein and Majuro B & C, RMI (<https://tidesandcurrents.noaa.gov/>) are used to derive rates of historical sea level change that coincide with the historical record of aerial imagery. Historical and future sea level rates are compared to determine time frames when future ASLR will accelerate beyond the historical rates.

Wave-driven flood and groundwater modeling at Kwajalein Atoll identify that at 0.4 m of ASLR, potable groundwater is lost after two consecutive years of wave overwash (Storlazzi et al., 2018). At 1.0 m of ASLR, infrastructure and agriculture soils are threatened as the majority (50%) of atoll islands are flooded annually (Storlazzi et al., 2018). The 0.4 and 1.0 m tipping points defined by Storlazzi et al. (2018) are compared to sea level threshold values derived from the geologic record.

4. Results and Discussion

4.1. Geological Record: Atoll Reef Island Formation and Middle to Late Holocene Sea Level Change

It has been proposed that in the latter stages of post-glacial SLR, reef flat progradation was initiated by reef accretion processes. As the rate of SLR decelerated, reduced accommodation space across the reef flat limited vertical accretion. Lateral reef accretion continued until 5,040 cal year BP at Jabat (Kench et al., 2014), 1,990 cal year BP at leeward Majuro (Yasukochi et al., 2014), and 3,790 cal year BP at windward Majuro (Figure 1a).

Table 2
Sea Level Threshold Values for Select Islands, Republic of the Marshall Islands

Island	Sea level threshold (m)		Future timing of island instability (years AD)			
	Max (island initiation)	Min (island stabilization)	Intermediate	Intermediate-high	High	Extreme
Jabat	0.65	1.1	2060–2100+	2050–2080	2040–2070	2040–2060
Leeward Majuro	1.05	0.70	2070–2100	2050–2080	2050–2060	2040–2060
Windward Majuro	0.75	0.60	2060–2080	2050–2060	2040–2050	2040–2050

Rotary drill cores reveal that the windward reef flat accreted laterally toward the lagoon, while the leeward reef flat expanded toward the ocean. Island emergence was initiated under increased hydrodynamic energy associated with elevated sea level (relative to present) at all three sites (Figure 1b). Coral gravel accumulated on the reef flat initiating the formation of an island core prior to the highstand (rising sea level) at Jabat (Kench et al., 2014), during the highstand at leeward Majuro (Yasukochi et al., 2014), and post-highstand (falling sea level) conditions at windward Majuro.

Islands rapidly expanded from a centralized core of sand and gravel as decreased wave energy and flow velocities associated with decelerating SLR and/or sea level fall, preferentially deposited very coarse to fine-grained *Calcarina* sediment (Figure 1c). Falling mid-Holocene sea level change facilitated an ecosystem shift where *Calcarina* foraminifera living in turf algae and macroalgal zones replaced living coral as the dominant reef flat habitat and island building sediment source (41–90% total island sediment) (Kench et al., 2014; Yasukochi et al., 2014).

Despite high sediment production at the reef flat (Fujita et al., 2009), further sea level fall in the late Holocene has exposed reef flats at low tide and essentially decoupled sediment delivery to islands. Under current conditions, reef islands are now reservoirs of relict, middle to late Holocene reef-derived sediment. Each island is presently adjusting to the new regime of ASLR with sedimentary processes largely confined to sediment recycling associated with spit and beach dynamics.

4.2. Deriving Place-Based Sea Level Thresholds and Time Frames for Island Destabilization and/or Resiliency

Local sea level thresholds (Table 2) for mid-Holocene island building at RMI were determined by comparing the geologic record of atoll island building to the middle to late Holocene sea level record (Figure 2a). Sea level threshold values are defined by the maximum and minimum sea level values that constrained initial island building and stabilization. Sea level thresholds constrain active island building between 0.65 and 1.10 m at Jabat, 0.70 and 1.05 m at leeward Majuro, and 0.60 and 0.75 m at windward Majuro.

Time frames of future island instability are estimated by comparing mid-Holocene sea level thresholds to four future sea level scenarios defined for Majuro (Figure 2b) by Sweet et al. (2017). The two lowest scenarios (low and intermediate-low) have been omitted from this study because they are exceeded by the current rate of global mean SLR, rendering them irrelevant. By the year 2100, the remaining four scenarios reach the following levels: intermediate (1.20 m); intermediate-high (1.91 m); high (2.64 m); and extreme (3.23 m). All scenarios predict that the mid-Holocene highstand value (1.14 ± 0.41 m; Table S3) will be exceeded prior to the end of the century. Within the next 80 years, all reef islands within RMI will be subjected to magnitudes of sea level greater than they have experienced since their formation during the middle to late Holocene. Thus, the geologic record is not used to predict ASLR impacts beyond a 1-m rise relative to the year 2000, but rather to predict a time frame for island instability based upon the fossil record. All islands are predicted to become permanently unstable between 2050 and 2090 (Table 2).

4.3. Re-Evaluating Time Frames of ASLR Impacts Using the Historical Record and Modern Observations and Modeling

Based upon the geological record alone, it is difficult to project future island stability beyond 1 m ASLR; thus, it is imperative to re-evaluate time frames of ASLR impacts using the historical record and modern observations and modeling. Historical studies provide a nearly 70-year record (1943–2010) of shoreline change and island area variability at 10 of the 34 atoll and mid-ocean reef platform islands (108 reef islands total) in RMI (Ford, 2012, 2013; Ford & Kench, 2015) (Table S1). During this time, the majority of islands either stabilized

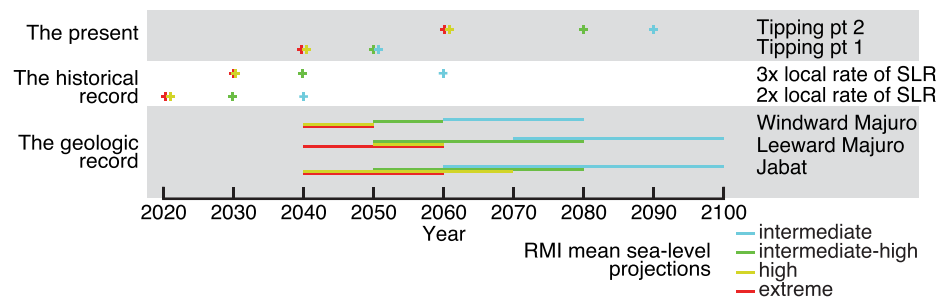


Figure 3. Time frame of ASLR impacts. Under the intermediate-high ASLR scenario, the first half of the century is characterized by a tripling in historical SLR at Majuro and the loss of potable groundwater (tipping point 1). As sea level rise exceeds 1 m (tipping point 2) in the second half of the century, sea level thresholds will be exceeded within decades. As islands grow increasingly unstable, (with no action) permanent island loss is inevitable.

or increased in area as the rate of ASLR equalled 1.96 ± 0.66 to 3.53 ± 1.80 mm/year at Kwajalein and Majuro, RMI, respectively (<https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>). These rates are comparable to the current global mean ASLR rate of 3.4 mm/year (<https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html>).

Unprecedented rates of ASLR are projected to accelerate, doubling the local (Majuro) relative long-term mean by 2020–2040 and increasing threefold by 2030–2060 (Sweet et al., 2017) (Figure 3). Although reef islands have been shown to exhibit a degree of physical resilience (Woodroffe, 2008), it is unclear if these dynamic island landforms will be able to adjust in the next 20–40 years to ASLR rates two to three times greater than historical rates. Furthermore, analyses of shoreline change since the 1970s have revealed that island loss (decreased area) at Wotje, Ebon, and Ujae (Table S1) has been attributed to accelerating ASLR or an unresolved shoreline oscillation (Ford, 2013; Ford & Kench, 2015).

Research centered on modeling present and near future wave dynamics implies that renewed island building due to enhanced sediment delivery will nonetheless leave islands uninhabitable due to aquifer salinization and damages to agriculture and infrastructure. At Kwajalein Atoll, Storlazzi et al. (2018) used wave-driven flood and groundwater models to identify two sea level tipping points. At 0.4 m of ASLR (tipping point 1), potable groundwater fails to recover after two consecutive years of wave overwash. At 1.0 m of ASLR (tipping point 2), the majority (50%) of the atoll islands are flooded annually by wave overwash, fully compromising the integrity of infrastructure and the agroforest. When applied across RMI, all islands are predicted to exceed tipping point 1 by 2040–2050 and tipping point 2 by 2060–2090 (Figure 3).

4.4. Using MIVA to Plan for Future SLR Impacts

In this study, we apply MIVA to ASLR scenarios presented by Sweet et al. (2017) in an attempt to capture uncertainty in future anthropogenic forcings and the physical mechanisms that govern future ASLR. The intermediate and extreme scenarios represent an updated analysis of the scientifically plausible lower and upper bounds on 21st century global mean ASLR. For low-lying atoll islands, we recommend that adaptive management planning reference the intermediate-high scenario as the most likely scenario. MIVA predicts under the intermediate-high scenario the following.

- Island formation and stabilization at Majuro Atoll required a drawdown in late Holocene sea level. Mid-Holocene SLR (0.2 mm/year) that triggered island formation at Jabat was an order of magnitude less than the current rate of SLR at the Majuro-C tide station (3.53 ± 1.8 mm/year; https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=720-017).
- Islands are already trending into declining stability due to ASLR as documented by published observations and modeling of extreme tides, wave inundation, salinization, and sediment mobilization.
- By midcentury, historical SLR at Majuro is projected to triple. Extreme tides and wave overwash will increase the frequency of temporary flood events resulting in the loss of potable groundwater and agroforests.
- As ASLR exceeds 1 m in the second half of the century, sea level thresholds will be exceeded within 10–20 years. Islands will be characterized by total loss of stability, and continued ASLR beyond mid-Holocene values (with no action) makes permanent island loss inevitable.

The application of MIVA at the RMI clearly demonstrates a growing instability of atoll islands prior to the end of the century. Island habitability due to accelerating ASLR will be increasingly threatened in the coming decades. All aspects of island instability are at risk by 2080 as ASLR exceeds mid-Holocene highstand values. It is clear from the geologic, historical, and modern observations and modeling that end of the century planning targets will provide no positive support for the resiliency of atoll islands and their people. Adaptive management strategies based upon impacts assessed by MIVA under the intermediate-high scenario need to be defined now and enacted in the near term.

Immediate, short term planning should acknowledge that the natural resilience of linked reef island sediment systems is a function of the ecological sensitivity of dominant sediment producers to environmental change. To ensure continued island maintenance by natural processes, it is imperative to improve understanding of the physical and ecological conditions that promote or limit island building. The growth and stability of carbonate-rich reef islands depend on the rate and pattern of sediment supply, which are functions of the local reef and reef flat ecology and governing hydrodynamic conditions (Woodroffe et al., 2007).

One of the largest gaps in knowledge in this field is the need for improved understandings of the biogeological linkages between coral reef ecosystems (sediment factories) and atoll reef islands (sediment reservoirs) (Dawson & Smithers, 2014; Woodroffe et al., 2007). Research at Heron Island, Australia (Scopéltis et al., 2011), Solomon Islands (Saunders et al., 2016), Palau (Van Woesik et al., 2015), and Sanya Bay, northern South China Sea (Chen et al., 2018), documents that increased water levels along shallow reefs have created greater accommodation space conducive to increased coral growth and colonization.

Pacific reef islands composed of a single sediment constituent such as a benthic foraminifera species maybe less resilient to climate stressors due to higher ecological sensitivity (Perry et al., 2011) to increased water depth (Fujita et al., 2009). Within RMI, islands are composed almost entirely (41–90%; Kench et al., 2014; Yasukochi et al., 2014) of *Calcarina* foraminifera living in turf algae and macroalgal zones along the fossil reef flats. Under accelerating ASLR, *Calcarina* will be replaced by renewed shallow coral-algal growth along fossil reef flats. Furthermore, anthropogenic inputs in the urban centers of Majuro have decimated modern *Calcarina* foraminifera populations (Fujita et al., 2009), removing the dominant source of sediment for island replenishment from the reef flat in these regions. Management actions should prioritize the preservation and restoration of natural coastal services provided by the reef and reef flat ecosystems at those islands that will retain their natural capacity to adjust to sea level over the coming decades (Duvat & Magnan, 2019).

As ASLR exceeds geologic thresholds, urban islands will be increasingly challenged to have plans in place that resolve the trade-off between ecological drivers that support natural island resiliency and development objectives (Mills et al., 2015). On short time scales, seawalls and land reclamation can contribute to reducing marine flood hazards; however, policies and planning are needed to ensure that engineered structures do not disrupt natural sediment pathways (Biribo & Woodroffe, 2013). Development and conservation can be achieved successfully by strategically developing coastal adaptation measures with consideration of current and future distribution of coastal ecosystems (Mills et al., 2015) that contribute to island maintenance and recovery from environmental stressors.

A more radical approach to adaptation supports in-country migration by raising the elevation of existing islands (Bordner et al., 2020) and constructing artificial islands (Brown et al., 2019). Although migration decisions across atoll nations have largely been driven by education, work, and healthcare (Kelman et al., 2019; van der Geest et al., 2020), within RMI, population-scale migration is not favored (Bordner et al., 2020). Instead, Marshallese leaders are committed to adapt in place to protect the sovereignty and identity of their people (Bordner et al., 2020). Hulmalé, an artificial island measuring 2.5 km² and 1.8 m high, was constructed in two phases beginning in the 1990s to support urban expansion in the Maldives. Flood exposure analyses have found that Hulmalé is projected to experience overtopping under 0.6 ± 0.2 m of SLR within the first half of this century and severe widespread flooding with 0.9 ± 0.2 m of SLR (Brown et al., 2019). Lessons learned from artificial island building in the Maldives have shown that once a reef flat system loses its ability to protect the coast through sediment replenishment and attenuation of wave energy, atoll nations are required to invest in the physical maintenance of their islands for the entirety of the island nation's existence. The MIVA approach developed in this study can be used to develop sea level thresholds and time frames to guide short- and long-term engineering goals.

To improve global atoll decision making, there is a need for standardizing methodology of historical aerial image analysis to strengthen shoreline data comparability and improve understandings of island dynamics. Duvat (2018) recommends employing two complementary geomorphic indicators: the use of the vegetation line, or stability line to document multidecadal atoll island change, and the base of the beach to detect SLR impacts. Inconsistencies in applying and reporting uncertainty when describing the significance of documented shoreline change rates and whole island area loss or gain need to be resolved. At a minimum, we recommend studies to account for uncertainty related to image resolution (pixel size), aerial photograph georeferencing, and shoreline digitization (Duvat & Pillet, 2017; Ford, 2012, 2013). Seasonal (swells, wind patterns) and tidal bias should also be reported (Fletcher et al., 2003) especially when using limited aerial image data sets. Further, studies proposing that atoll islands form during conditions of post-glacial SLR (and therefore more resilient to ASLR) have relied upon survey measurements that do not report horizontal or vertical uncertainties. The fundamental paleosea level resolution of these data sets is problematic because vertical accuracy and resolution are not accounted for. Additionally, we recommend workers to establish a high acceptance threshold for the fundamental indicativeness of geologic proxies representing sea level.

Regarding adaptation to ASLR, the indigenous values embodied in island cultural identity are based on location and grow out of a millennial history of survival as a community. Moreover, the modern economic and global security values embodied in the sovereign nationhood of atoll republics are similarly based on strategic mid-ocean location. Such place-based values eliminate the option of population-scale migration as a solution to ASLR as it will lead these values to transition from stability to instability. Steps to successfully adapt to ASLR include building policy, recognition, and support for populations that prefer to stay in place (Farbotko et al., 2020), foremost among which is the preservation of physical location. Across the Pacific, successful community-based adaptation initiatives have been tailored to local culture and livelihoods, support adaptive capacity building, define community based upon local ecosystems and resources, and simultaneously address climatic and non-climatic livelihood pressures (McNamara et al., 2020). Faced with extinction of their place, and the values that radiate from it, atoll island communities possess an inherent moral authority in the planetary emergency of climate change and sovereignty over their decision making.

5. Conclusions

In conclusion, MIVA derives sea level thresholds and time frames of instability from a 5,000-year record of island evolution. Here we show that all reef islands studied in the RMI are experiencing unprecedented rates of ASLR (1.96 ± 0.66 to 3.53 ± 1.80 mm/year) relative to mid-Holocene SLR (0.2 mm/year) that triggered island formation at Jabat Island. For low-lying atoll islands, we recommend the use of the intermediate-high scenario as the most likely model of projected ASLR. Under the intermediate-high ASLR scenario, island habitability is threatened by the mid-21st century due to the accelerating rate of ASLR (three times local mean) and the loss of potable groundwater and loss of a viable agroforestry. By 2080, permanent island loss is plausible as ASLR exceeds mid-Holocene highstand values. Impacts are expedited in more extreme scenarios of ASLR.

The application of MIVA at the RMI clearly depicts that adaptation to ASLR for atoll islands needs to start now and should target pre-century to midcentury threats to island habitability. End of the century planning goals and ASLR targets suggested by prior studies are no longer realistic. The drivers of ASLR are increasingly likely to grow due to committed warming from past emissions (Mauritsen & Pincus, 2017), accelerated rates of warming (Xu et al., 2018), rapidly narrowing carbon budgets to stop warming at 1.5°C (IPCC, 2018), and projections of continued greenhouse gas emissions over the next few decades (Newell et al., 2019). Furthermore, there is evidence that ASLR could exceed 2 m by 2100 due to rapid warming of Greenland and West Antarctic ice sheets (Bamber et al., 2019; Sweet et al., 2017).

Adaptive management actions should first prioritize the preservation and restoration of reefs and reef flat ecosystems that protect the coast through sediment production, delivery, and attenuation of wave energy. Urban islands that have exceeded anthropogenic tipping points (Duvat & Magnan, 2019) and no longer retain natural forms of resiliency will require engineering and physical maintenance for the perpetuity of their existence. Coastal structures and development will require policies and planning that retain longshore sediment transport and availability for island maintenance.

Understanding the future evolution and stability of atoll islands requires a multitemporal, interdisciplinary approach. ASLR impacts are much greater than the loss of remote islands, or disruptions in an islands' ability to naturally evolve with the rising tide. ASLR threatens the cultural identity and political sovereignty of island nations. ASLR, like all climate-related impacts, is a complex physical, social, and dynamic issue that requires adaptable planning methods, transdisciplinary research, and an open-minded, multiworld view approach that fosters the ensured existence of people's identity.

Data Availability Statement

Data used in this study, including supporting information, will be made publicly available on the University of Hawai'i School of Ocean and Earth Science and Technology Scholar Space (<https://scholarspace.manoa.hawaii.edu/handle/10125/25982>).

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