Development of a World-Wide Database of Atoll Morphometrics

Enter authors here: Faith M. Johnson[1] and Alejandra C. Ortiz[2,1]

[1]Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695

[2]Department of Geology, Colby College, Waterville, ME 04901

Corresponding author: Alejandra C. Ortiz (acortiz@colby.edu)

Key Points:

- Global Atoll Morphometric Database created for 154 Atolls, 3,795 motu, and 596 reef flats
- Development python code for automated morphometric analysis of satellite imagery of atolls
- For all motu larger than 1 km (n = 725), consistent reef-flat width in front of motu of 188 ± 156 m

Abstract

Small Island Nations are at considerable risk of climate change impacts from sea-level rise to coral acidification to increasing cyclone intensity; understanding how they will change in the coming century is vital for climate mitigation and resiliency. Atoll morphometrics are calculated for 3,795 motu and 593 reef flats on 154 atolls. The total land (motu) area is 1,836.55 km^2 with a total reef flat area of 7,387.43 km^2. A consistent methodology to classify, segment, and calculate morphometrics is used. Composites are created for 4 years (2015- 2018), and are classified into motu, reef flat, open water/lagoon via unsupervised classification. Morphometrics are computed for each motu and reef flat of the atoll in python, creating a database of atolls and their associated morphometrics. Consistency in processing removes spatial and user bias, enabling a better understanding of geographic patterns of atolls. We identify trends in atoll, motu, and reef flat formations. The average atoll reef flat width is 850 ± 817 m and the average motu width is 263 ± 210 m. Distinct differences in the distribution of motu can be seen on a regional scale in French Polynesia, while globally, wider reef flats with larger motu are found closest to the equator. Globally there is a consistent reef flat width in front of large motu (> 10 km length) of 188 ±156 m. Our atoll morphometric database creates a baseline of current atoll characteristics that can be expanded upon in the future and used for evaluating temporal changes to atoll islands.

Plain Language Summary

To understand what will happen to small island nations under climate change, we must understand the current state of these islands. We have created a method in python code to automatically take a satellite image of an atoll, a tropical island where an old reef surrounds an inner lagoon with small islets (motu) on top, and classify into land, water, and reef. Our code then automatically measures characteristics of these landscapes like the area of each motu (islet) or the width of each reef-flat for 3,791 motu and 593 reef flats on 154 atolls. In French Polynesia, there is a consistent pattern of large motu appearing on the north and eastern side of the atoll with a narrower total reef-flat width found on these sides. Globally, a consistent reef-flat width in front of the motu is found to be 188 ± 156 m. These measurements allow a current snapshot atoll measurements, which can be used as a baseline to track potential impacts of climate change by measuring changes to these landscapes over time.

1 Introduction

The sub-aerial land found atop atoll carbonate reef platforms, known as reef islands, islets, motu, and cays, often serve as the only home to terrestrial ecosystems and human infrastructure on remote island nations. Despite their essential role, the morphologic processes shaping and forming these islets remain poorly understood. Morever, a consistent method for measuring their current morphometrics is lacking (Duvat, 2019). To predict the response of these island nations to rising sea levels and other climate change impacts (Barnett & Adger, 2003; Fletcher & Richmond, 2010; Kumar, 2020), we must first create a baseline of planform land area and a reproducible method for measuring change.

We create a series of python scripts utilizing Google Earth Engine and Landsat imagery to measure atoll morphometrics such as motu area or reef-flat width. Our robust methodology employs open-source software and allows for a consistent approach to calculating planform terrestrial area of these island nations and a path for measuring and tracking changes to these landscapes over time. By investigating the regional and global patterns of atoll morphometrics along with previous hydrodynamic modeling (Ortiz & Ashton, 2019), we develop a conceptual model to explain differing pathways of motu and reef flat evolution.

1.1 Background

Atolls are found in tropical oceans, consisting of a carbonate reef platform (hereafter called reef flat) surrounding a central lagoon with subaerial islands on top of the reef (hereafter called motu) (Schlager & Purkis, 2013). We use a broad and inclusive definition of an atoll: a carbonate reef-platform encircling or partially surrounding a central lagoon (which may or may not be filled in), emplaced upon may be subaerial landforms. With this broad definition, our atoll database includes 623 atolls, easily subsetted down based on a range of factors (e.g. only atolls containing motu); this broad definition was done to ensure that all possible island forms are captured in our analysis (Figure 1).

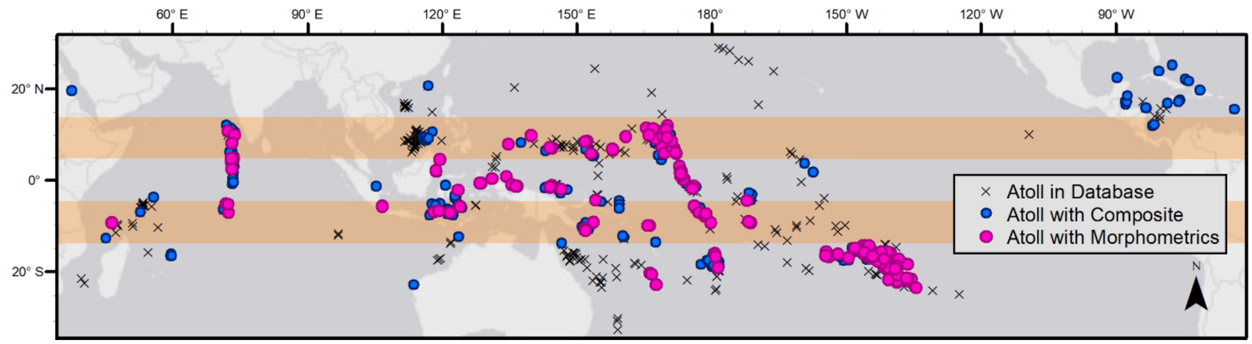


Figure 1. Map of atolls worldwide showing locations of atolls in database (black x), atolls with composite imagery created from Landsat (blue dots), and atolls with both composite imagery and morphometrics calculated (pink dots), separated into equatorial (0°-4.7° latitude), mid tropical (4.7° - 14° latitude) highlighted in beige strips, and high tropical (14° - 27° latitude).

Atolls are formed from coral reefs growing on subsiding dormant volcanic islands (Darwin, 1842) and are shaped though global changes in sea levels (Daly, 1925; M. R. Toomey et al., 2016). Motu (aka cays or islets) are composed of carbonate sand, coral shingle, and rubble perched on top of the conglomerate reef flat encircling the inner lagoon (Woodroffe et al., 1999). Similar to Ortiz and Ashton (2019), we do not limit the term motu to only islets comprised of particular sediment sizes as suggested by some authors (Brander et al., 2004; Paul Simon Kench et al., 2017; Richmond, 1992) as the distinction varies across papers. Motu form and evolve on a shorter time scale, decades to centuries (Paul Simon Kench, Owen, et al., 2014; Perry et al., 2013; C D Woodroffe et al., 1999), than the atoll itself, millennia to hundreds of thousands of years (M. Toomey et al., 2013; M. R. Toomey et al., 2016). Motu initiation, formation, and evolution has occured under current (Paul Simon Kench, Chan, et al., 2014; Sengupta et al., 2021), rising (Paul S Kench et al., 2005; McLean & Kench, 2015a; Webb & Kench, 2010), and falling sea level conditions (Colin D. Woodroffe et al., 2007). Evolution of motu can be episodic, with island change tied to specific events such as a tropical cyclone that added sediment to the system (Duvat & Pillet, 2017) or land reclamation from human activities (Aslam & Kench, 2017a; Duvat & Magnan, 2019; Duvat & Pillet, 2017; M. Ford, 2011).

Atolls are at risk from climate change due to their low-lying nature; many atolls have a maximum elevation of less than 5 m. Accelerated rates of sea-level rise (SLR) may outpace vertical reef flat accretion from the coral reefs. In addition, storm driven flooding will be increased by climate change (Storlazzi et al., 2015) driving increased flooding and inundation from swell waves generated by distant storms (Hoeke et al., 2013; Shope et al., 2017). Ocean acidification and other oceanographic stressors such as changing ocean temperature can reduce sediment production from the coral reefs putting the ability of motu and reef platforms to keep pace with SLR further at risk (Eyre et al., 2018). To understand the potential response of these landforms to changing climate risks, we must first understand the processes driving their evolution and their current state.

Although atolls are often described as circular or annular structures, their morphology varies widely. The controls on atoll shape are poorly understood and inconsistently quantified. Previous work by Stoddart (1965) used hand tracing of 99 atolls to measure their shape, demonstrating a “fundamental homogeneity of atoll shapes” including a tendency for elongated and more elliptical atolls rather than the often described ring-shape. Our methods recreate these measurements both at the atoll scale and at the individual motu or reef-flat scale, enabling further study of atoll island change and comparison between current and previous measurements.

Many studies of atoll geomorphology use a combination of field and remote sensing technologies, including historic aerial photography and modern satellite imagery, ranging from a focus on one motu to a regional group of atolls. Frequently studies have relied on hand digitation of shorelines and atoll morphology (Duvat & Pillet, 2017; M. R. Ford & Kench, 2014, 2015; Paul Simon Kench, Chan, et al., 2014; Sengupta et al., 2021; Webb & Kench, 2010). Different features are used as a proxy for the shoreline location including edge of vegetation (Albert et al., 2016a; M. R. Ford & Kench, 2015; Garcin et al., 2016)), defining a stability line (Duvat & Pillet, 2017), using a GPS track at the time of the field work (Paul Simon Kench, Chan, et al., 2014), using supervised classification (Holdaway et al., 2021), and using an image analysis software with hand digitation to fix any errors (Schlager & Purkis, 2013). Studies looking at changes in land area or shoreline position on atolls include (Albert et al., 2016b; Aslam & Kench, 2017b; Duvat & Magnan, 2019; Duvat & Pillet, 2017; Paul S Kench et al., 2018; McLean & Kench, 2015b; Nunn et al., 2020). Ford and Kench (2014) examined changes on Nadikdik Atoll in the Marshall Islands using remote sensing data from 1945-2010. Using the edge of vegetation, as proxy for shoreline, they found a net increase of island area including the formation of a new island from an initial deposit of sediment to a stable island with vegetation.

Duvat (2019) re-analyzed 20 different papers studying atoll land area change for 30 atolls (709 islands). They found that 88.6% of the islands were stable (within +/- 3% area change) or increased in area over the time period of analysis. All the larger islands (> 0.1 km^2) were either stable or increased in area. A key aspect of this paper is the collation of other studies and comparison atoll island changes across decadal changes. One of their stated future research priorities is to create a common assessment protocol to strengthen data comparability, which our research directly addresses. Holdaway et al. (2021) leveraged large amounts of available satellite imagery to quantify atoll land area change for 221 atolls. Similar to our procedure, they created temporal composites of atolls from Landsat imagery with a mix of multiyear and annual composites. Supervised classification, with a fluctuating number of landcover classes, was used to segment the images. For comparison between all the sites, a binary land/water class was created and total land area change was calculated on an atoll level. From 2000 – 2017, land area increased 6.1% for the 221 atolls, primarily in the Maldives and South China Sea mainly due to land reclamation (Holdaway et al., 2021).

Numerical modeling work by Ortiz and Ashton (2019) found that the width of the reef-flat in front of motu (the distance from the oceanside of the motu to the edge of the oceanside of the reef-flat) should reach an equilibrium distance dependent on the offshore wave climate.

Using the open-source model XBeach in hydrodynamic mode, they investigated the potential response of sediment transport with the presence of a 1D motu to changing offshore wave climate and changing reef-flat widths in front of the motu. They found that once motu are present on the reef flat (i.e. once there sub-aerial land blocking the reef-flat from the lagoon), the motu would grow and accrete oceanward (thus narrowing the oceanside motu to reef-flat width) up to a certain point where the direction of sediment transport would reverse and direct sediment offshore. Their conceptual model predicts self-organization of motu prograding oceanwards to a critical reef-flat width dependent on the offshore wave height. 2D modeling by Shope and Storlazzi (2019) found that that atoll islands orientated parallel to the deep-water wave direction would accrete towards the lagoon while eroding along shorelines exposed to direct wave action.

While there are many studies of atolls island evolution, there is a critical need to establish a baseline of atoll morphometrics using a consistent methodology. The aim of this research is to create a reproducible approach to evaluate atoll morphology on a broad spatial scale using satellite imagery and innovative data processing techniques. We use a constant time frame for the temporal composites, an automated classification technique to separate the atoll into parts (motu, reef flat, open water/lagoon), automatically segmenting the classified imagery, and calculating morphometrics on each object. We create a worldwide database of atolls and their morphometrics. This methodology removes spatial bias and enables a better understanding of current geographic patterns in atoll morphometrics and potentially identify first order patterns between atolls.

2 Materials and Methods

Our code is built on open-source software within python using common libraries in image analysis (i.e. Google Earth Engine, skimage, and pandas) to create temporal composites, classify into three landcover classes, and segment into objects for morphometric analyses. We have created a suite of python scripts with discrete morphometric calculating functions, available on GitHub (AtollGeoMorph), that other users can adapt for their own morphometric analysis. For each atoll, a temporal composite is created then classified into land, water, or reef-flat using k-means unsupervised classification. These landcover classes are then segmented and analyzed for a variety of morphometrics including area, width, centroid, and length (Figure 2). From these morphometrics, we calculate atoll-scale averages as well as bin by cardinal position on the atoll. Our database allows easy comparison at the individual atoll-scale, object-scale (i.e. comparing all the motu widths measured), the regional scale (patterns of motu widths in French Polynesia), or globally.

2.1 Composites and Classification

Four-year temporal composites (2015 - 2018) are created from Tier 1 Landsat Images using the Google Earth Engine library (GEE) in python similar to the methodology used by Ortiz et al. (2017). For a given atoll, all Tier 1 Landsat images available from 2015-2018 are collected, cloudy pixels are removed using in-built GEE cloud removal functions, and the remaining pixels from each image are composited using the 50th percentile on a per-pixel per-band basis. Tier 1 Landsat images are georectified, have atmospherically corrected surface reflection, and have a 30 meter resolution (Google Earth Engine Team, 2015). Six bands (blue, green, red, NIR, SWIR1, and SWIR2) are retained in our final temporal composite. A count band indicating the number of images used for the composite in each pixel and a mask band to show the geometry given to GEE are also included. This composite is saved as a geotiff for easy access by other scripts. The temporal composite method has been used by other researchers as it can remove issues of cloudiness in a given Landsat image, a very common issue for Atolls (Mateo-García et al., 2018; Ortiz et al., 2016).

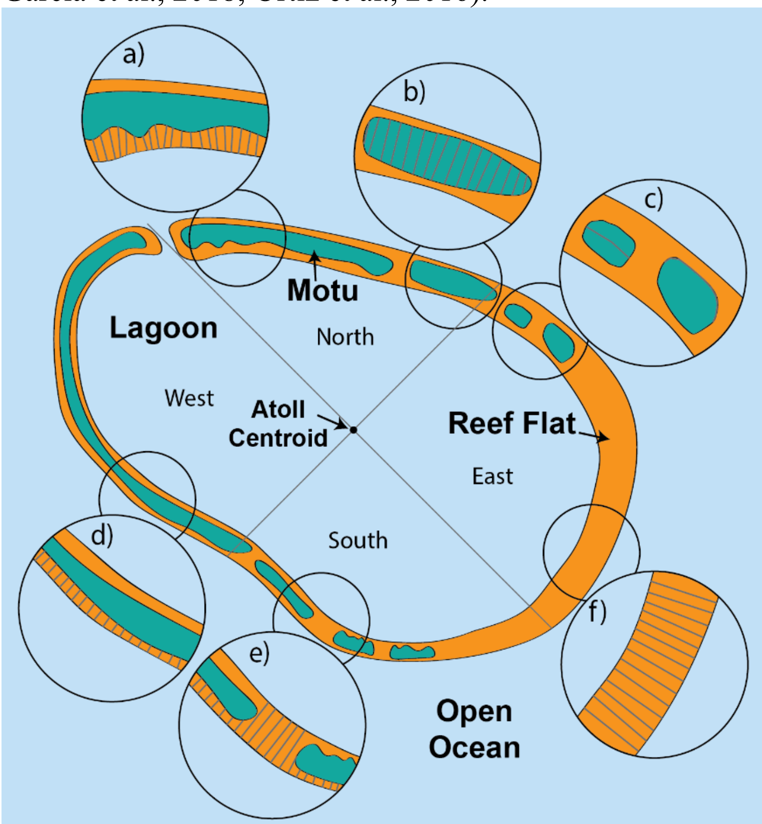


Figure 2. Conceptual diagram of morphometrics calculated for idealized atoll classified into three landcovers: green (subaerial land, motu), orange (reef flat), and blue (water). A) Motu to lagoon-side reef-flat width (herein called lagoon reef width), b) motu width, c) motu length, d) motu to ocean-side reef-flat width (herein called ocean reef width), e) effective reef-flat width, and f) total reef-flat width (assuming no land on top, herein called reef-flat width). Approximate location of center of mass of entire atoll object denoted by atoll centroid with resultant segregation of atoll objects by cardinal directions North, East, South, and West shown.

We assume that the primary landcover classes on an atoll are reef flat, motu (land), and water and use k-means clustering for automated classification. The mask from the composite is used to remove any edge issues or other nearby atolls. Given Landsat's medium resolution (30 m), the classified image is cleaned by removing small groups with less than 8 isolated pixels (objects < 7,200 m^2 are not analyzed). All motu smaller larger than 7,200 m^2 but smaller than 57,600 m^2 (64 isolated pixels), only have basic morphometrics calculated (area, perimeter, and location), while motu larger than 64 pixels have complex morphometrics calculated (such as width and length). The total area across our entire database accounted for by motu between .72 and 5.7 hectares, 8-64 connected pixels (n = 2,036), is less than 3% of the total area (47 km^2) measured by the remaining large motu (n = 1,753, 1,789 km^2). The morphometric analysis is run on the cleaned classified temporal composite with all the resultant data saved in pandas dataframes and as CSV files.

2.2 Morphometrics

A methodology for determining atoll morphometrics is created and implemented in python scripts, publicly available on GitHub (https://github.com/ale37911/AtollGeoMorph). Our python scripts are split into three distinct pieces: 1) create temporal composites (Section 2.1), 2) classify, clean, and segment the image then calculate morphometrics (Section 2.2), and 3) collate saved outputs from each atoll into larger dataframes for analysis and visualization (Section 3.3). For detailed description of the methods used in the morphometric analysis see Supporting Information Text S1.

Once classified, the number and approximate location of lagoons is input by the user. Users manually close the lagoon for cases where automated lagoon finder is unable to match the lagoon number. Morphometrics of the lagoons are calculated: area, perimeter, all the perimeter points (on a per-pixel basis), and the centroid. Atoll level morphometrics are also calculated: outside atoll perimeter (ocean perimeter), the atoll centroid, and shape factors used by Stoddart (1965). Area, perimeter, and centroid of each object (i.e. reef flat or motu) are calculated and stored in pandas dataframe where each row is the perimeter point per object (motu or reef flat) basis. All points are classified as an ocean-side or lagoon-side point based on relative distances to the lagoon or ocean.

For each point, several morphometrics are calculated from an exposure angle to a cardinal position angle along with multiple widths within each object, i.e. width of a motu or total width of a reef-flat per point from ocean-side to lagoon-side, or between objects, i.e. width from motu ocean-side point to reef-flat ocean side points called ocean reef width (Figure 2, Figure S1). The width code utilizes a list of points for calculating the width (i.e. ocean-side perimeter points of a motu), the associated shoreline exposure angles for those points, and a list of points the width will be calculated to (i.e. lagoon-side perimeter points for the same motu). It finds the nearest perpendicular point (i.e. on the lagoon side) within a range of degrees, assuming a default 15°.

The length of each motu is calculated using the center points of motu width measurements (Figure 2). The motu length is calculated as the cumulative distance along that line. The ocean-side and lagoon-side lengths are also. For the reef length, the ocean side length is used as proxy for the length. Since the reef flat ocean side points may not be in order, any points that are more than 3 pixels apart are skipped in the length sum. After processing the motu, reef flat, and lagoon data frames are saved to CSV and excel spreadsheets.

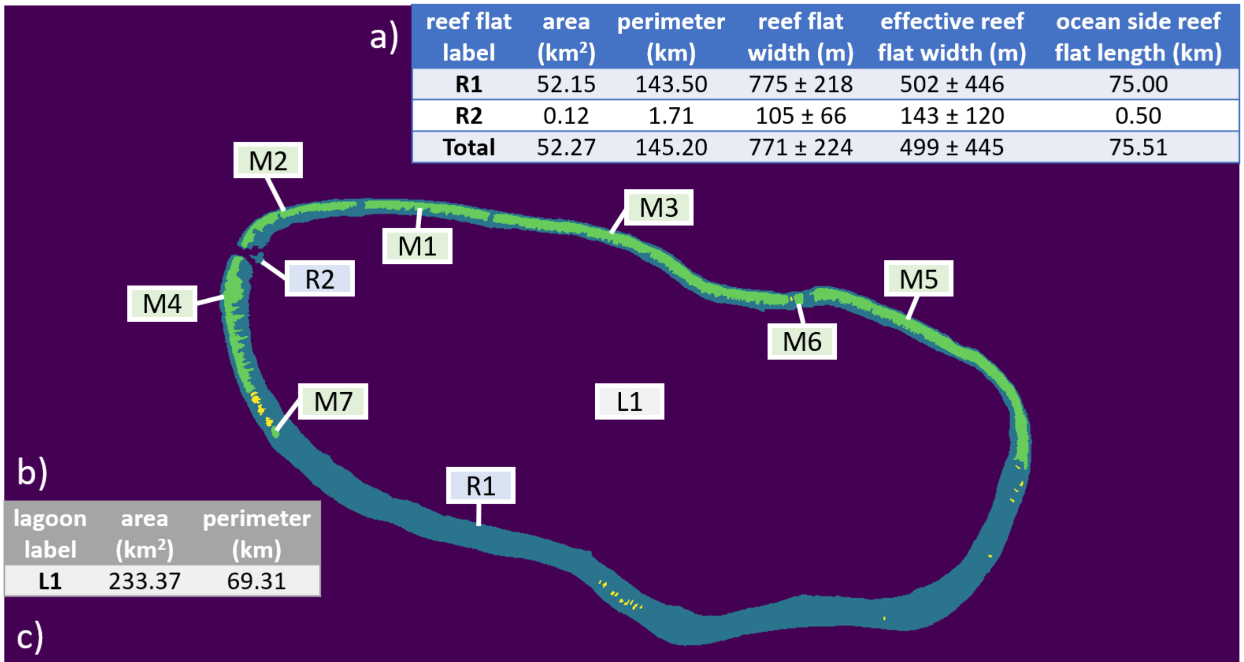
2.3 Analysis at range of Scales

Atolls are analyzed individually, regionally, and globally with morphometrics summarized at a per-point, per-object, and per-atoll level. At the region level, morphometrics are also binned by cardinal direction relative to the atoll centroid (positioning angle), while at the global scale morphometrics are binned by absolute latitude. Summary tables are created for each atoll that include at least the area, mean widths, length, centroid location, cardinal directional bin (positioning angle bin) most of the object is in for each of motu, reef flat, and lagoon object. By using pandas dataframes, it is relatively easy to summarize the data based on different grouping criteria such as latitude or country or even selected atoll names. We have selected several methods for analyzing our dataset but expect that other groupings could be used to identify patterns in the database. Primary morphometrics for all 154 atolls analyzed are available as a table (Table S1). In addition, the code to create all morphometrics are available (AtollGeoMorph).

3 Results

There are 623 atolls in our inclusive atoll database. There is adequate Landsat coverage to create a composite for 385 of those atolls, of which we calculate morphometrics for 154 (Figure 1). We started with an inclusive list of atolls including some with no motu (fully submerged reefs), interior islands in the lagoon (i.e. Bora Bora, French Polynesia), or that had very small or completely filled in lagoons (i.e. Nikunau, Kiribati). While we were able to create a composite for some of these atolls, they were not included in the morphometrics calculations. Results are presented for Faaite Atoll in French Polynesia, regionally for French Polynesia, and globally for all atolls analyzed.

3.1 Atoll Scale Results: Faaite Atoll, French Polynesia



a)

reef flat label	area (km²)	perimeter (km)	reef flat width (m)	effective reef flat width (m)	ocean side reef flat length (km)
R1	52.15	143.50	775 ± 218	502 ± 446	75.00
R2	0.12	1.71	105 ± 66	143 ± 120	0.50
Total	52.27	145.20	771 ± 224	499 ± 445	75.51

b)

lagoon label	area (km²)	perimeter (km)
L1	233.37	69.31

c)

motu label	area (km²)	perimeter (km)	motu width (m)	ocean reef width (m)	lagoon reef width (m)	motu length (km)	ocean side motu length (km)	lagoon side motu length (km)
M1	1.17	10.46	243 ± 57	79 ± 22	216 ± 86	4.77	4.54	5.99
M2	1.07	10.76	244 ± 83	81 ± 32	346 ± 112	4.71	5.56	5.30
M3	3.44	25.73	299 ± 46	76 ±21	176 ± 75	11.19	11.17	14.77
M4	1.71	15.72	291 ± 135	139 ± 42	392 ± 135	5.33	5.90	10.35
M5	3.55	24.92	319 ± 66	73 ± 29	208 ± 102	11.13	11.73	13.62
M6	0.10	1.16	207 ± 135	106 ±38	152 ± 75	0.41	0.39	0.79
M7	0.07	1.21	152 ± 57	244 ± 53	689 ± 178	0.44	0.45	0.84
Small	0.36	8.71						
Total	11.48	98.67	287 ± 85	88 ± 41	250 ± 142	37.97	39.73	51.66

Figure 3. Faaite atoll, French Polynesia object level data. Background image is K-means classified with individual objects labeled: motu are green (all morphometrics calculated) and yellow (small motu, only basic morphometrics calculated), reef flat are blue, and water is purple. Motu are labeled starting with M, reef flats with R, and the lagoon with L. This letter is followed by the index number assigned north to south for each class of object based on the northern most point of that object. Morphometric summary tables are included for a) reef flats, b) lagoons, and c) motu. Error in the mean widths is one standard deviation.

Faaite Atoll, French Polynesia is in the Pacific Ocean at 16.758°S, 145.238°W (Figure 3). The atoll has one lagoon, two reef flats, and 27 motu. Faaite has a total lagoon area of 233.37 km^2, reef flat area of 52.27 km^2, and land area (motu area) of 11.48 km^2. The two reef flats are unequal in size with the primary reef flat accounting for more than 99% of the total reef flat area (Figure 3a). The large standard deviation on the effective reef flat width measurements for Faaite occurs because the distribution of widths is not unimodal. Seven of the motu are large enough to calculate length and width measurements (Figure 3c). Similar to many atolls in our database, the lagoon-side motu length is longer than the ocean-side motu length (6/7, Figure 3c). This is exemplified in M4, where the lagoon-side motu length is 75% longer than the ocean-side motu length, as the lagoon side shoreline is more crenulated than the ocean-side shoreline. We see that the larger motu (plotted in green, Figure 3) are distributed on the northern shoreline while the smaller motu (only simple morphometrics, plotted in yellow Figure 3) are found mostly on the southern shorelines. To quantify this observation, we also bin all morphometrics relative to relative cardinal position on the atoll (Figure S1, Figure 4).

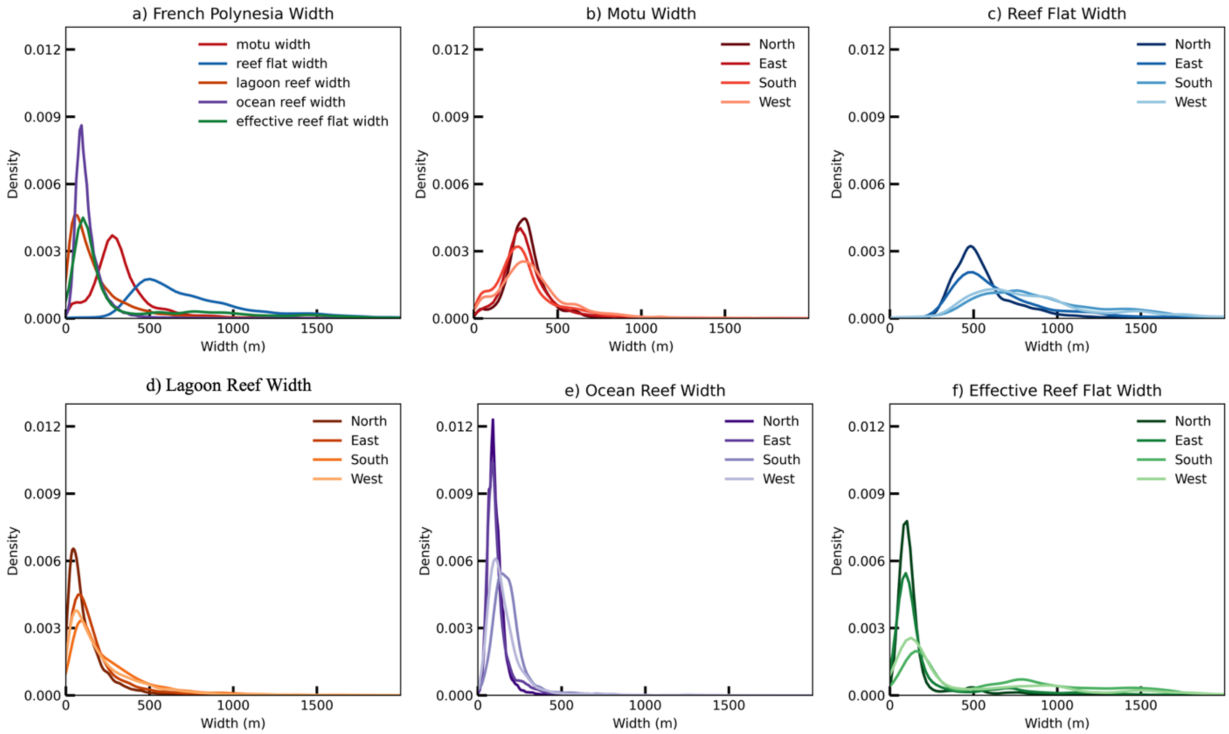


Figure 4. Density functions for width calculations in French Polynesia on a per-point basis. a) Atoll wide widths, binned by cardinal directions for b) motu width, c) total reef flat width, d) lagoon reef width, e) ocean reef width, and f) effective reef flat width.

3.2 Regional Scale Results: French Polynesia

There are 60 atolls in French Polynesia with sufficient Landsat coverage to create a temporal composite and calculate morphometrics. These atolls are located between 14° 24' S-23° 21' S and 134° 29' W- 154° 41' W. These atolls have 1,930 motu (837 full morphometrics) and 80 reef flats (Table S1). In French Polynesia, there is on average 1.3 reef flat per atoll with the number of motu ranging from as few as 1 to as many as 69 and an average of 14 larger motu per atoll. 75% of the reef-flat length is blocked by motu length.

On a per-point basis, the ocean reef width has the narrowest distribution (Figure 4a&e) and the total reef width has the widest distribution (Figure 4a&c). When breaking out the data by cardinal position on the atoll, we see a clear trend that the northern shoreline consistently has the smallest range of widths while the south and west tend to have the widest range of measurements. When looking at motu width, ocean reef width, and lagoon reef width, there is a strong unimodal distribution (Figure 4d&e). However, in the south and west direction, the reef flat width measurements show a bimodal behavior (Figure 4c&f).

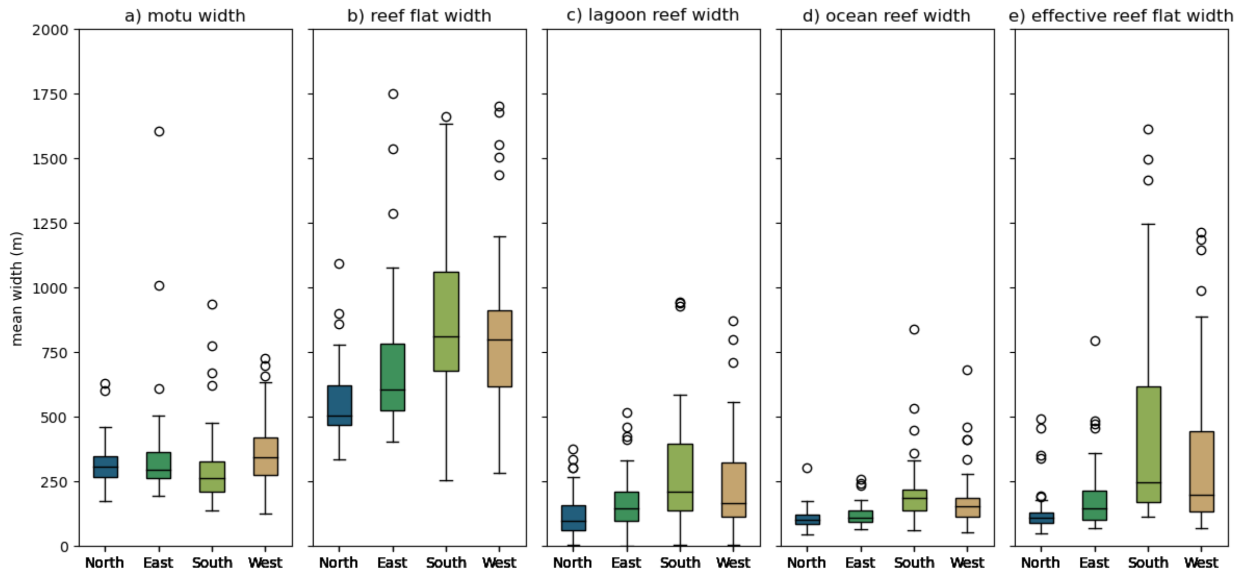


Figure 5. Cardinal position within the atoll binned widths in French Polynesia on a per-atoll basis for a) motu width, b) reef flat width, c) lagoon reef width, d) ocean reef width, and e) effective reef flat width. One point per atoll is the mean width. Not shown on total reef flat width (b), two outliers: one point at 2,790 m in the South bin and one at 2,320 m in the West bin.

On a per-atoll basis (one data point per-bin per-atoll), small and large atolls are weighted equally (Figure 5 and Figure 6). Median motu width range from 263 m in the south to 345 m in the west (Figure 5a). The reef flat width is narrower in the north and east and wider in the south and west with the largest variation in the south (Figure 5b). This trend is also observed in the effective reef flat width, with the narrowest width in the north and the largest in the south (Figure 5e). The lagoon reef width (Figure 5c) is more variable than the ocean reef width (Figure 5d). The north has the narrowest lagoon reef width of 100 m and the narrowest ocean reef width at 101 m. The south bin has the widest widths for both the mean lagoon reef width and the mean ocean reef width at 212 m and 184 m respectively.

Table 1. Median with one standard deviation per atoll cardinal position binned for French Polynesia motu and reef-flat morphometrics.

Cardinal Position	Ocean Reef Width (m)	Motu Width (m)	Lagoon Reef Width (m)	Reef Flat Width (m)	Effective Reef Flat Width (m)	Motu Length (km)	Length Blocked By Motu (%)
NORTH	101± 34	308 ± 77	100 ± 66	504 ± 85	109 ± 34	10.6 ± 1.33	96.2
EAST	108 ± 46	296 ± 98	145 ± 95	607 ± 175	147 ± 72	11.5 ± 1.80	95.1
SOUTH	185 ± 64	263 ± 103	212 ± 120	812 ± 123	248 ± 159	3.1 ± 0.47	51.8
WEST	154 ± 64	345 ± 148	166 ± 103	799 ± 168	200 ± 123	4.6 ± 1.22	75.3

The east and the north shores have the longest motu while the south and west have shorter ones (Figure 6a). The north and the east have different morphometrics that reflects the longer motu lengths including the tighter distribution of width measurements for the ocean reef width reflecting less potential edge effects (Figure 4e). The north and east sides also have a larger percent of their lengths covered by motu (Figure 6b). In the north and east a larger percentage of the motu blocking access to the lagoon, and the overall reef flat width is narrower (Table 1). Overall, in French Polynesia the north and east shores have longer motu and narrower reef flats for all reef measurements (reef flat width, lagoon reef width, ocean reef width, and effective reef flat width) compared to the south and west shores.

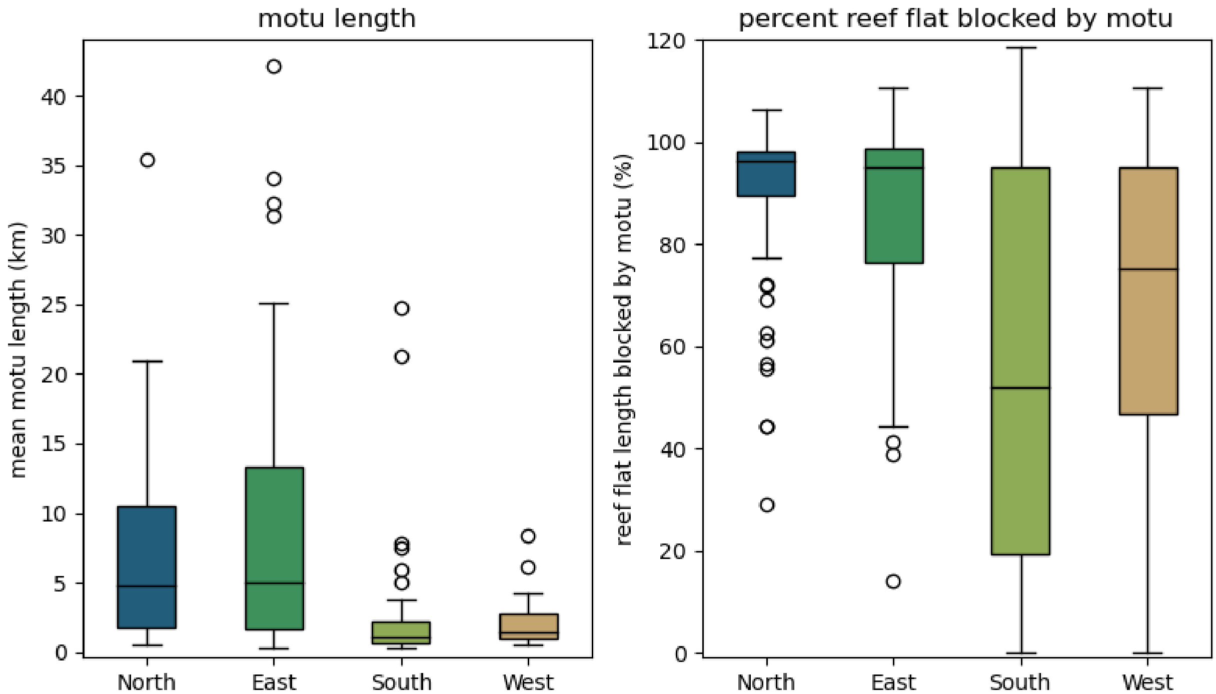


Figure 6. Binned directionally per-atoll mean motu length for French Polynesia Atolls. If a motu crosses in to more than one bin it is included in the bin where it has the greatest number of ocean points. b) Percent length of reef flat covered by motu separated by cardinal directional bin.

3.3 Global Scale Results

Morphometrics are calculated for 154 atolls (Figure 1). Overall, there are 3,795 motu (1,753 with all morphometrics calculated) and 596 reef flats (Table 2). The total land (motu) area is 1,836.55 km^2 and the total reef flat area is 7,387.43 km^2.

Table 2. Median morphometrics with one standard deviation per atoll binned by latitude for all atolls.

Bin	Atoll #	Motu #	Reef Flat #	Motu Area (km^2)	Reef Flat Area (km^2)	Motu Length (km)
LOW	31	184/395	118	3.8 ± 1.09	34.9 ± 0.31	3.9 ± 1.23
MID	57	695/1416	351	0.8 ± 0.49	20.1 ± 6.25	2.4 ± 1.06
HIGH	66	874/1994	127	2.9 ± 1.37	22.3 ± 0.60	8.8 ± 4.01
ALL	**154**	**1753/3795**	**596**	**2.7 ± 0.98**	**27.4 ± 2.18**	**3.9 ± 2.10**

Atolls are binned by their absolute latitudes, with the least number of atolls in the equatorial latitudes (Table 2). The equatorial atolls are located from 4.7°S to 4.7°N, the mid tropical atolls are from 14°S to 4.7°S and 4.7°N to 14°N, and the high tropical atolls are located greater than 14°S and 14°N. The high tropical atolls are all located in the Pacific Ocean in the southern hemisphere and are dominated by the atolls of French Polynesia (n=60/66). The equatorial atolls have the least number of motu and reef flats per atoll with an average of 12.7 motu (5.9 motu with all morphometrics) and 3.4 reef flats. Mid tropical and high tropical atolls have an average 24.4 motu (12.0 motu) and 6.1 reef flats, and 30.2 motu (13.1 motu) and 9.0 reef flats respectively.

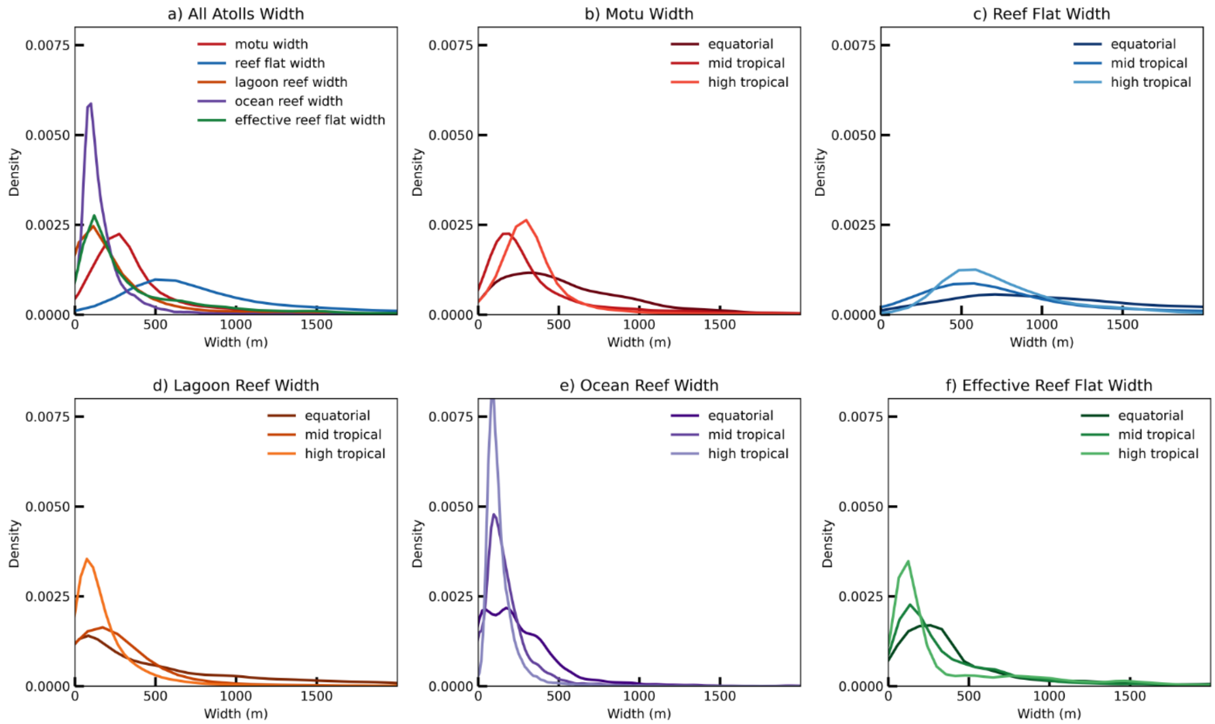


Figure 7. Density function of width measurements for all atolls on a per-point basis grouped by latitude. a) atoll wide widths, b) motu width, c) total reef flat width, d) lagoon reef flat width, e) ocean reef flat width , and f) effective reef flat width.

The ocean reef width has the narrowest distribution of widths indicating that it varies the least across all atolls (Figure 7a). The total reef flat width has the widest distribution. Equatorial atolls consistently have lower peak densities, and thus have a wider distribution of widths compared to our other two groups of atolls (Figure 7b-f). High tropical atolls have the narrowest distributions of widths. The mid tropical atoll morphologies lie between the equatorial and high tropical atolls with motu width and ocean reef width more closely aligned with the high tropical atolls, while the effective reef flat width and lagoon reef width more closely match the equatorial atolls. Ocean reef width for the equatorial atolls has a bimodal distribution with a skew toward wider widths. Conversely, both mid and high tropical atolls show unimodal distributions (Figure 7e). The equatorial atolls also exhibit distinctly more skew towards wider motu (Figure 7b).

Mid tropical atolls have a narrower distribution of motu length than either equatorial or high tropical atolls although their motu length peaks between them (Figure 8). High tropical atolls have their peak length at a shorter motu length than the mid tropical or equatorial atolls. When width is considered, the high tropical atolls have a narrower distribution of widths for the longer motu (Figure 8c) as compared with larger distribution seen with the equatorial atolls (Figure 8a).

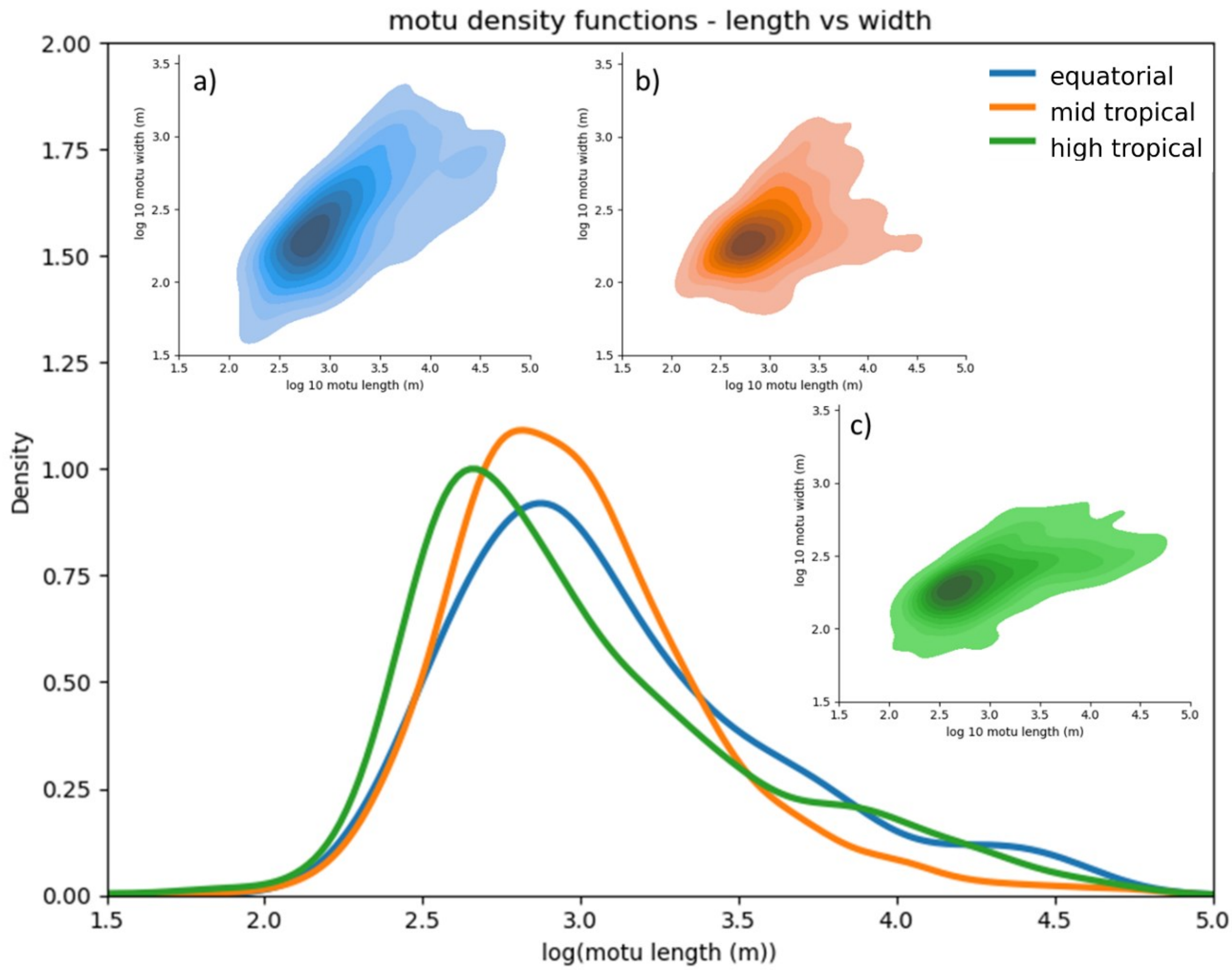


Figure 8. Density function of motu length for all atolls on a per-motu basis grouped by latitude, with 2D distribution of motu length and motu area for a) equatorial (blue), b) mid tropical (orange), and c) high tropical motu (green).

4 Discussion

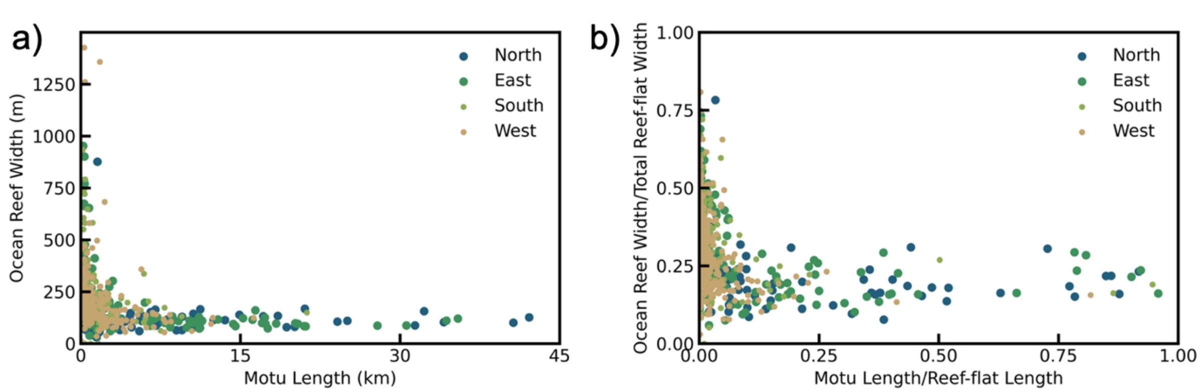


Figure 9. a) Reef flat width in front of motu (ocean reef width) vs motu length for each motu in French Polynesia classified by cardinal position on the atoll. b) Reef flat width in front of the motu normalized by the width of the reef

flat the motu is on vs the motu length normalized by the length of the reef flat the motu is on classified by cardinal position on the atoll. Each point represents one motu.

On a per-object basis, the ocean reef width (reef width in front of the motu) reaches a near constant width once the motu reaches a certain length (Figure 9 and 10). For all French Polynesia motu longer than 1 km, the ocean reef width is 150 ± 110 m (n = 324/837), however the error drops into a quarter if we only look at motu longer than 10 km while the average reef-flat width in front of the motu remains similar (108±25 m, n=54/837) (Figure 9a). There are clear trends of increased numbers of large motu on the Northern and Eastern shores (52% and 45% respectively compared to only 29% and 36% on the Southern and Western sides), with starker differences for the longest motu > 10 km (10-17% on N and E, with only 1-2% on S and W). The relative ocean reef width in front of the motu (Figure 9b) was calculated to ensure that smaller overall atoll footprints were not excluded. The same trend of a constant ocean reef width is exhibited again, dominated by Northern and Eastern motu (blue and green dots, Figure 9b). For motu that occupy more than 10% of the total reef-flat length, there is an average of 18% of the reef-flat width in front of the motu (n = 97/837), with the majority (68/90) of these motu found on the N and E shores (70%). For smaller motu, i.e. with lengths < 1 km, the mean ocean reef width is similar, 202 ± 138 m, but with larger variation in ocean reef flat widths. The consistent pattern of near constant width in front of motu implies that self-organization may be driving a critical reef-flat width for French Polynesia.

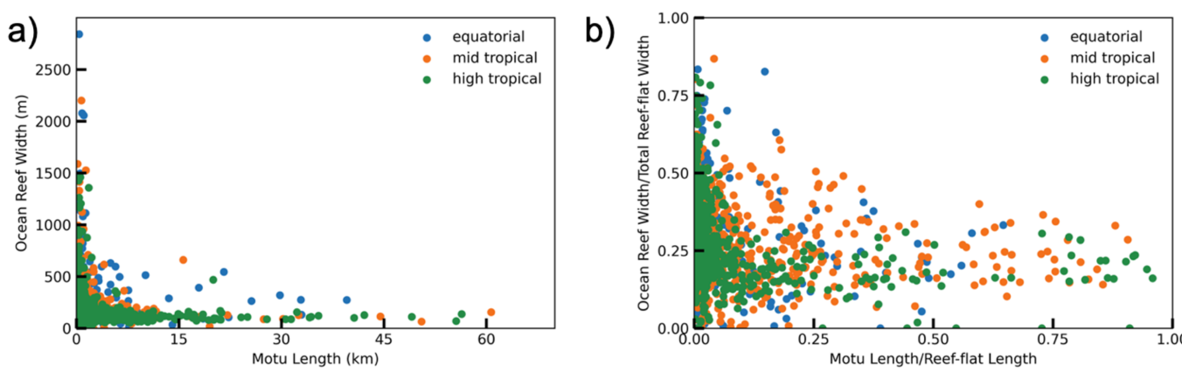


Figure 10. a) Reef flat width in front of motu (ocean reef width) vs motu length on a per motu basis classified by latitude. b) Reef flat width in front of the motu normalized by the width of the total reef flat under the motu vs the motu length normalized by the length of the reef flat the motu is on classified by latitude. Each point represents one motu classified as Equatorial Atolls (blue): 0° to 4.7°, Mid tropical atolls (orange): 4.7° to 14°, and High tropical atolls (green): greater than 14°.

This trend of a critical reef-flat width continues when looking at our global morphometrics of motu (Figure 10). For all motu > 1 km in length, the mean ocean reef width is 184 ± 156 m (n=725/1753); and as the motu increase in length (> 10 km), the error decreases to a mean ocean reef width of 142 ± 106 m (n=89/1753) (Figure 10a). There are variations between our different groups of atolls, with the equatorial atolls exhibiting a larger and more variable critical reef-falt width for all large motu (>1 km), 282 ± 273 m, compared to the mid and high tropical atolls, 193 ± 140 m and 150 ± 111 m respectively (Figure 10a). However, when we normalize the motu by the size of the atoll (Figure 10b), we find that for motu occupying > 10% of the total reef-flat length, the ocean reef width is about 22% of the total reef-flat width (n=331/1753). Increasing the cutoff for only motu that occupy at least 25% of the reef flat length, the averages remain the same across all atoll groups (equatorial: 23%, mid tropical: 25%, and low tropical: 17%) but the errors decrease, as seen earlier with French Polynesia (Figure 9b). Our results highlight that the equatorial atolls have wider reef-flats dominated by larger motu, but still about a 5th of the reef-flat width remains open in front of all large motu across our 154 atolls. This trend of a near constant reef-flat width in front of the motu implies that there maybe an equilibrium ocean reef width in front of large motu as suggested by Ortiz and Ashton (2019) modeling in Xbeach. A key assumption to their conceptual model is that the motu modeled were long-enough to not be affected by flow around the motu into the lagoon; thus long motu are the best natural proxy.

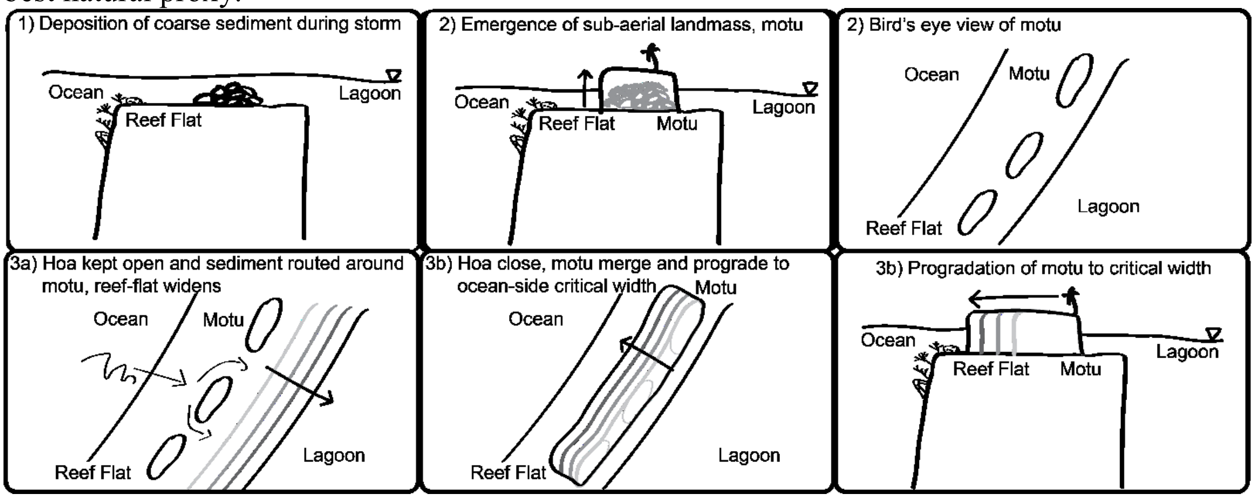


Figure 11. Conceptual model of motu formation and evolution on the reef flat adapted from Ortiz and Ashton (2019) from initial motu creation and emergence (1-2) to divergence of motu evolution leading to widening of the underlying reef-flat (3a) or narrowing of the motu to ocean side reef flat (ocean reef width) with elongated motu (3b).

Using the data generated, we quantify motu and reef flats morphometrics as well as tease out potential patterns in morphology and possible causes. Building upon Ortiz and Ashton's (2019) conceptual model of motu formation and evolution, we propose an updated model to account for varying patterns seen globally in our dataset (Figure 11). Motu formation starts with the deposition of coarse sediment near the mid-point of the reef-flat evolving to a sub-aerial landmass (Figure 11.1-2). Once there are several motu along a section of reef flat, the system may evolve in two ways. If the motu stay separate, i.e. the shallow channels between the motu (also called by the Polynesian term, hoa) stay active, the sediment supply from ocean-side reefs will cause the reef flat to prograde towards the lagoon and widen over time (Figure 11.3a). If the motu merge, such that sediment can no longer pass to the lagoon around the motu, that same sediment supply should prograde the motu oceanwards as predicted by Ortiz and Ashton's XBeach modeling (Figure 11.3b). The progradation and widening of the motu will continue until the reef flat in front of that motu reaches a critical width (our measurement of ocean reef width). The proposed conceptual model is one explanation for the lagoon vs ocean shoreline length differences found that were discussed for Faaite. As motu merge both shorelines will be sinusoidal, but as the ocean side prograde the shoreline will start to smooth and parallel the shoreline of reef flat on the ocean-side, while the lagoon side will stay sinusoidal.

When a motu is long enough, the distance from the motu to the ocean-side reef flat reaches a near constant width (Figure 9&11). When considered directionally, the northern and eastern shores of the French Polynesia atolls consistently have more motu that are considerably longer (10-11 km) and block a larger percentage of the reef flat (95-96%) than the south and western sides (3-4.5 km and 52-75%, Table 1). Moreover, the total reef flat tends to be narrower as does the ocean reef width (critical reef-flat width in front of the motu) on the N and E compared to the S and W with less variability in the measurements (Figure 5 and Table 1). While on the Southern and Western sides, the reef flat width has a bimodal distribution with a secondary peak occurring at a wider width of ~1.5 km (Figure 4c). As the north and east have around 95% of the reef flat length blocked by motu, with only 52% percent blocked in the south, there is a clear correlation between length of motu blocked and reef flat width.

While our database covers an extensive range of atolls and morphometrics, it is limited to almost half of the available temporal composites created. In addition, another 100-200 locations, typically considered atolls (Bryan, 1953; Goldberg, 2016), are not currently measured here due to lack of available quality composites. Only atolls with sufficient Landsat coverage had temporal composites created, and some atolls with a more fractal-like morphology (i.e. parts of the Maldives) were not able to be run in our morphometric code. This resulted in using atolls primarily from the Pacific Ocean that have clearly defined lagoons. We are also biased towards larger motu due to the 30m resolution of the Landsat imagery and the size of motu and reef flat necessary to run the full morphometric code. Lastly, several assumptions are made in our current code that limit it's flexibility from assuming that the most numerous area in our composite is water to assuming that there are only three dominant landcover classes and that k-means unsupervised classification is the best method for classifying our image.

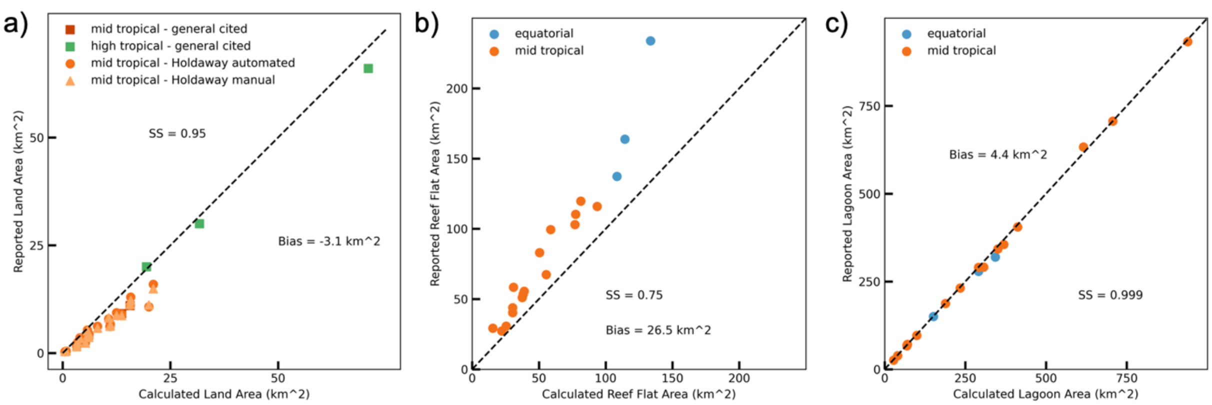


Figure 12. Validation of per-atoll morphometrics comparing calculated to previously reported morphometrics for a) total land area, b) total reef-flat area, and c) total lagoon area with calculated Skill Score (SS) and Bias and 1:1 line (black dashed).

In order to validate our methodology, we compared the calculated morphometrics presented in this paper with values reported in previous studies on atolls (Figure 12). Similar to Holdaway et al. (2021), we performed this validation at the atoll area scale using the bias (mean error between previously reported morphometrics and our calculated morphometrics) and Brier Skill Score (estimate of error in our morphometrics to variance of previously reported morphometrics) (Gharagozlou et al., 2020). Our estimates of both reef-flat area and lagoon area (Figure 12b&c) are consistently under-predicting the area with a bias of 26.5 km^2 and 4.4 km^2 respectively. However, our morphometrics over-predict total land area per atoll on average by

3.1 km^2 (Figure 12a). All our estimates of total area per atoll have an excellent Brier Skill Score and follow reported previous landcover areas well.

5 Conclusions

We have developed a global database of atolls along with a methodology to systematically create temporal Landsat composites and measure morphometrics of three landcover classes (land, water, and reef flats). Our code enables quick and easy comparison between different scales of our database from investigating the variability in motu morphometrics at a single atoll to a regional grouping to a global analysis. With the use of pandas dataframes, all the morphometrics can be grouped based on shoreline orientation, relative position on the atoll, or per-object. We have highlighted several potential binning methods to analyze the patterns found in our database (such as using the relative position on the atoll for exploring the spatial heterogeneity of motu distributions in French Polynesia by segregating into N, E, S, and W). Distinct and quantifiable differences were shown in the location of motu on atolls within a region (French Polynesia) and globally based on latitude. The code to create composites and measure morphometrics is available for other researchers to employ. This automated analysis will allow for the direct comparison of data, providing one possible answer to Duvat and Magnan's call for research priority of creating a common assessment protocol. Further research includes extending the analysis of our dataset by comparing the morphometrics with potential drivers such as waves, storms, and anthropogenic activities to explain differences in the behavior for either directionality for a specific regions or different latitudes (i.e. in French Polynesia wave climate and directionality of the motu widths, presence on the reef flat).

Acknowledgments

The authors acknowledge funding from the Southeast Climate Adaptation Science Center for F. Johnson Global Change fellow. F. Johnson was primarily responsible for data curation, formal analysis, software development, visualization, and writing the original draft. A. Ortiz was primarily responsible for conceptualization of the project, funding acquisition, investigation, methodology development, validation, project administration and supervision, and reviewing and editing this paper. The authors would like to thank Sean Daly for the initial creation of the inclusive Atoll Database.

Open Research

All software used in this project is open-source and freely available. Only freely available Landsat imagery was used for each atoll composite. All python scripts referenced herein is available on the Github repository AtollGeoMorph. All the code needed to create the data visualization in Figures 5-10 and 12 is also available on the AtollGeoMorph Github repository. All tables created can be extracted from the csv files generated by these scripts.

References

Albert, S., Leon, J. X., Grinham, A. R., Church, J. A., Gibbes, B. R., & Woodroffe, C. D. (2016a). Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environmental Research Letters*, *11*(5), 054011.

Albert, S., Leon, J. X., Grinham, A. R., Church, J. A., Gibbes, B. R., & Woodroffe, C. D. (2016b). Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environmental Research Letters*, *11*(5), 054011.

Aslam, M., & Kench, P. S. (2017a). Reef island dynamics and mechanisms of change in Huvadhoo Atoll, Republic of Maldives, Indian Ocean. *Anthropocene*, *18*, 57–68.

Aslam, M., & Kench, P. S. (2017b). Reef island dynamics and mechanisms of change in Huvadhoo Atoll, Republic of Maldives, Indian Ocean. *Anthropocene*, *18*, 57–68.

Barnett, J., & Adger, W. N. (2003). Climate Dangers and Atoll Countries. *Climatic Change*, *61*(3), 321–337. https://doi.org/10.1023/B:CLIM.0000004559.08755.88

Brander, R. W., Kench, P. S., & Hart, D. (2004). Spatial and temporal variations in wave characteristics across a reef platform, Warraber Island, Torres Strait, Australia. *Marine Geology*, *207*(1–4), 169–184. https://doi.org/http://dx.doi.org/10.1016/j.margeo.2004.03.014

Bryan, E. H. Jr. (1953). A Check List of Atolls. *Atoll Research Bulletin*, (19), 1–38.

Daly, R. A. (1925). Pleistocene changes of level. *American Journal of Science*, (58), 281–313. https://doi.org/10.2475/ajs.s5-10.58.281

Darwin, C. (1842). *On the Structure and Distribution of Coral Reefs: Being the First Part of the Geology of the Voyage of the Beagle Under the Command of Captain Fitzroy, RN During the Years 1832 to 1836*. Smith, Elder.

Duvat, V. K. E. (2019). A global assessment of atoll island planform changes over the past decades. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(1), e557.

Duvat, V. K. E., & Magnan, A. K. (2019). Rapid human-driven undermining of atoll island capacity to adjust to ocean climate-related pressures. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-51468-3

Duvat, V. K. E., & Pillet, V. (2017). Shoreline changes in reef islands of the Central Pacific: Takapoto Atoll, Northern Tuamotu, French Polynesia. *Geomorphology*. https://doi.org/https://doi.org/10.1016/j.geomorph.2017.01.002

Eyre, B. D., Cyronak, T., Drupp, P., de Carlo, E. H., Sachs, J. P., & Andersson, A. J. (2018). Coral reefs will transition to net dissolving before end of century. *Science*, *359*(6378), 908–911.

Fletcher, B. C. H., & Richmond, B. M. (2010). *Climate Change in the Federated States of Micronesia: Food and Water Secutiy, Climate Risk Management, and Adaptive Strategies*. Retrieved from http://seagrant.soest.hawaii.edu/sites/default/files/publications/1webfinal_maindocument_climatechangefsm.pdf

Ford, M. (2011). Shoreline Changes on an Urban Atoll in the Central Pacific Ocean: Majuro Atoll, Marshall Islands. *Journal of Coastal Research*, 11–22. https://doi.org/10.2112/JCOASTRES-D-11-00008.1

Ford, M. R., & Kench, P. S. (2014). Formation and adjustment of typhoon-impacted reef islands interpreted from remote imagery: Nadikdik Atoll, Marshall Islands. *Geomorphology*, *214*, 216–222. https://doi.org/10.1016/j.geomorph.2014.02.006

Ford, M. R., & Kench, P. S. (2015). Multi-decadal shoreline changes in response to sea level rise in the Marshall Islands. *Anthropocene*, *11*, 14–24. https://doi.org/https://doi.org/10.1016/j.ancene.2015.11.002

Garcin, M., Vendé-Leclerc, M., Maurizot, P., le Cozannet, G., Robineau, B., & Nicolae-Lerma, A. (2016). Lagoon islets as indicators of recent environmental changes in the

South Pacific–The New Caledonian example. *Continental Shelf Research*, *122*, 120–140.

Gharagozlou, A., Dietrich, J. C., Karanci, A., Luettich, R. A., & Overton, M. F. (2020). Storm-driven erosion and inundation of barrier islands from dune-to region-scales. *Coastal Engineering*, *158*, 103674. https://doi.org/10.1016/J.COASTALENG.2020.103674

Goldberg, W. M. (2016). ATOLLS OF THE WORLD: REVISITING THE ORIGINAL CHECKLIST. *Atoll Research Bulletin2*, (610).

Hoeke, R. K., McInnes, K. L., Kruger, J. C., McNaught, R. J., Hunter, J. R., & Smithers, S. G. (2013). Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, *108*, 128–138.

Holdaway, A., Ford, M., & Owen, S. (2021). Global-scale changes in the area of atoll islands during the 21st century. *Anthropocene*, *33*, 100282.

Kench, Paul S, McLean, R. F., & Nichol, S. L. (2005). New model for reef-island evolution: Maldives, Indian Ocean. *Geology*, *33*.

Kench, Paul S, Ford, M. R., & Owen, S. D. (2018). Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nature Communications*, *9*(1), 605. https://doi.org/https://doi.org/10.1038/s41467-018-02954-1

Kench, Paul Simon, Owen, S. D., & Ford, M. R. (2014). Evidence for coral island formation during rising sea level in the central Pacific Ocean. *Geophysical Research Letters*, *41*(3), 820–827. https://doi.org/10.1002/2013GL059000

Kench, Paul Simon, Chan, J., Owen, S. D., & McLean, R. F. (2014). The geomorphology, development and temporal dynamics of Tepuka Island, Funafuti atoll, Tuvalu. *Geomorphology*, *222*, 46–58. https://doi.org/10.1016/j.geomorph.2014.03.043

Kench, Paul Simon, Beetham, E., Bosserelle, C., Kruger, J., Pohler, S. M. L. M. L., Coco, G., & Ryan, E. J. J. (2017). Nearshore hydrodynamics, beachface cobble transport and morphodynamics on a Pacific atoll motu. *Marine Geology*, *389*, 17–31. Retrieved from https://www.sciencedirect.com/science/article/pii/S0025322716303668

Kumar, L. (Ed.). (2020). *Climate Change and Impacts in the Pacific*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-32878-8

Mateo-García, G., Gómez-Chova, L., Amorós-López, J., Muñoz-Marí, J., & Camps-Valls, G. (2018). Multitemporal Cloud Masking in the Google Earth Engine. *Remote Sensing*, *10*(7), 1079. https://doi.org/10.3390/rs10071079

McLean, R., & Kench, P. (2015a). Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews: Climate Change*, *6*(5), 445–463. https://doi.org/10.1002/wcc.350

McLean, R., & Kench, P. (2015b). Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews: Climate Change*, *6*(5), 445–463.

Nunn, P. D., Kumar, L., McLean, R., & Eliot, I. (2020). Islands in the pacific: Settings, distribution and classification. In *Springer Climate* (pp. 33–170). Springer. https://doi.org/10.1007/978-3-030-32878-8_2

Ortiz, A. C., & Ashton, A. D. (2019). Exploring carbonate reef flat hydrodynamics and potential formation and growth mechanisms for motu. *Marine Geology*, *412*, 173–186. https://doi.org/10.17605/OSF.IO/R3J2D

Ortiz, A. C., Roy, S., & Edmonds, D. A. (2016). Marsh collapse by pond expansion on the Mississippi River Delta Plain. *Nature Geosciences*, *submitted*.
Ortiz, A. C., Roy, S., & Edmonds, D. A. (2017). Land loss by pond expansion on the Mississippi River Delta Plain. *Geophysical Research Letters*, *44*(8), 3635–3642. https://doi.org/10.1002/2017GL073079
Perry, C. T., Kench, P. S., Smithers, S. G., Yamano, H., O'Leary, M., & Gulliver, P. (2013). Time scales and modes of reef lagoon infilling in the Maldives and controls on the onset of reef island formation. *Geology*, *41*(10), 1111–1114. https://doi.org/10.1130/G34690.1
Richmond, B. M. (1992). Development of atoll islets in the central Pacific. In *Proceedings of the 7th international coral reef congress* (Vol. 2, pp. 1185–1194).
Schlager, W., & Purkis, S. J. (2013). Bucket structure in carbonate accumulations of the Maldive, Chagos and Laccadive archipelagos. *International Journal of Earth Sciences*, *102*(8), 2225–2238. https://doi.org/10.1007/s00531-013-0913-5
Sengupta, M., Ford, M. R., & Kench, P. S. (2021). Shoreline changes in coral reef islands of the Federated States of Micronesia since the mid-20th century. *Geomorphology*, *377*, 107584.
Shope, J. B., & Storlazzi, C. D. (2019). Assessing morphologic controls on atoll island alongshore sediment transport gradients due to future sea-level rise. *Frontiers in Marine Science*, *6*, 245.
Shope, J. B., Storlazzi, C. D., & Hoeke, R. K. (2017). Projected atoll shoreline and run-up changes in response to sea-level rise and varying large wave conditions at Wake and Midway Atolls, Northwestern Hawaiian Islands. *Geomorphology*, *295*, 537–550. https://doi.org/https://doi.org/10.1016/j.geomorph.2017.08.002
Stoddart, D. R. (1965). The shape of atolls. *Marine Geology*, *3*.
Storlazzi, C. D., Elias, E. P. L., & Berkowitz, P. (2015). Many atolls may be uninhabitable within decades due to climate change. *Scientific Reports*, *5*, 14546.
Toomey, M., Ashton, A. D., & Perron, J. T. (2013). Profiles of ocean island coral reefs controlled by sea-level history and carbonate accumulation rates. *Geology*, *41*(7), 731–734. https://doi.org/https://doi.org/10.1130/G34109.1
Toomey, M. R., Ashton, A. D., Raymo, M. E., & Perron, J. T. (2016). Late Cenozoic sea level and the rise of modern rimmed atolls. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *451*, 73–83.
Webb, A. P., & Kench, P. S. (2010). The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change*, *72*. https://doi.org/10.1016/j.gloplacha.2010.05.003
Woodroffe, C D, McLean, R. F., Smithers, S. G., & Lawson, E. M. (1999). Atoll reef-island formation and response to sea-level change: West Island, Cocos (Keeling) Islands. *Marine Geology*, *160*(1–2), 85–104.
Woodroffe, Colin D., Samosorn, B., Hua, Q., & Hart, D. E. (2007). Incremental accretion of a sandy reef island over the past 3000 years indicated by component-specific radiocarbon dating. *Geophysical Research Letters*, *34*(3), L03602. https://doi.org/10.1029/2006GL028875