Supplementary Material

Development of World-Wide Database of Atoll Morphometrics

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# Methods for Atoll Morphometrics

Once the temporal composite is classified, the number and size of lagoons present on the atoll is given by user input. An automatic lagoon finder uses morphometric opening and closing to connect adjacent reef flats. If the automatic (unsupervised) lagoon finder is unable to find the correct number of lagoons, the user clicks pairs of points to close gaps between reef flats to create the lagoon perimeter. These points are saved in a text file to ensure reproducibility. Morphometrics of the lagoons are calculated including area, perimeter, all the perimeter points (on a per-pixel basis), and the centroid. Atoll level morphometrics are also calculated including 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).

To determine if a perimeter point is an ocean or a lagoon side point, the closest distance to an atoll ocean or lagoon point is calculated. For each object (motu or reef flat), the perimeter points closest to the ocean and to the lagoon are determined and subtracted from the ocean and the lagoon distances respectively, creating relative distances, allowing for proper classification of points for motu positioned close to the edge of the reef flat (on the ocean or lagoon side). Each point is then classified as an ocean or lagoon point based on the relative distance. Points classified as ocean are checked to ensure that a line from that point to the closest atoll ocean point does not cross the object. If it does, that point is reclassified as a lagoon point. The points for each motu object are filtered to have a continuous ocean and a continuous lagoon side with the points in spatial order. This filtering is not performed on the reef flat objects because there may be multiple lagoon and ocean segments based on the number of lagoons.

Several angles are calculated for each perimeter point. The shoreline exposure angle is the angle normal to the shoreline of the object that is pointing away from the lagoon towards the ocean. The cardinal positioning angle is the angle from the centroid of the atoll to the point in question. This cardinal positioning angle is used to create four bins (north, east, south, and west) and used when analyzing atoll level morphometrics.

The widths calculated for each motu are motu width, ocean reef width (reef flat width in front of the motu), and lagoon reef width (reef flat width behind the motu). The widths calculated for the reef flat are reef flat width and effective reef flat width (width from the ocean to the closer of either the motu or lagoon) (Figure S1).The width code takes a list of points that the width will be calculated from, the exposure angle associated with those points and a list of points the width will be calculated to. The code finds the nearest point within a certain degree of normal (default 15°). The near normal width is used unless it is more than x times longer than the closest distance (default x is twice the distance). Motu width is measured from the ocean side to lagoon side motu points with an x of four times the distance (Figure S1). Ocean reef flat width is measured from ocean side motu points to ocean side reef flat points and the lagoon reef flat width is measured from lagoon side motu points to lagoon side reef flat points (Figure S1). For the ocean reef flat width and lagoon reef flat width, any width measurement that crossed another motu or itself is replaced with not a number (nan). Reef flat width is measured from ocean side to lagoon side reef flat points. Effective reef flat width is measured from ocean side reef flat points to the lagoon side of the reef flat unless a motu is in the way in which case it is measured to the ocean side of the motu in question. The closest point ±7° of normal is used unless that distance is more than 10 times the closest point. If the effective reef flat width is found to cross any motu, the closest width is used instead.

The length of each motu is calculated using the center points of motu width measurements. The center points are rounded to the nearest two pixels and connected into a line removing any loops. The motu length is calculated as the cumulative distance along that line (Figure 2c – yellow line). The length is also calculated along the ocean side and the lagoon side points (Figure 2c – pink and purple line respectively). 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, removing points between adjoining reef flat pieces and any jumps between sections of the reef. An example of the final summarized per atoll level output is shown in Table S1, detailing the total landcover area for every atoll analyzed (154).

At the atoll scale, the total area of the atoll (assuming that the reef-flat is enclosed around the lagoon) is a strong predictor of the atoll perimeter (Figure S2). While there is variation for all our atolls, we can estimate the atoll perimeter as: where *A* is the atoll area (Figure S2a). This means that an atoll with an area of 100 km2 should have a perimeter of 48.96 km. For the 7 atolls with an area of 100 ± 10 km2, the mean perimeter is 49.28 km.

# Shape Factors

We also take the outer shape of the atoll form itself, and calculate a range of morphometrics used in calculating the shape factors by Stoddart (1965). Using the *regionprops* function from the python library *skimage.measure*, we automatically calculate the area (*A*) and perimeter (*P*) of the atoll. In addition, the major and minor axis length of the ellipse with the same normalized second central moments as the atoll itself (*L1* and *L2* respectively) is extracted. These values are used in the calculation of our shape factors, using the approach detailed in Stoddart (1965) and in Güler et al. (2021) new PolyMorph-2D plugin for GIS morphometric analysis. The shape factors calculated and graphed are Horton’s Form Factor (1932) - *F*, Miller’s Circularity Ratio (1953) - *Rc*, Schumm’s Elongation Ratio (1956) – *Re*, and the Ellipticity Index (1965) – *Ie*. All of these shape factors provide a non-dimensional ratio of the overall polygonal shape of the atoll, allowing us to estimate the shape complexity and circularity.

Horton’s Form Factor (1932) was initially used to describe the outline forms of drainage basins and watersheds and is the ratio of the area of the object to the major axis length squared such that: . Where *A* is the measured area of the object and *L1* is the length of the major axis of the ellipse. *F* is equal to unity when the object is a square and approximately 0.78 when it is a perfect circle. Smaller values of F indicate a more elongated polygon.

Miller’s Circularity Ratio (1953) was initially created by Cox (1927) for analyzing particle shape to describe the circularity or compactness of a polygon. It is defined as the ratio of the area of the object to the area of a circle with the same perimeter as our object such that: . Where *A* is the area of the object and *P* is the perimeter of the object. In this case, unity means a perfectly smooth circle for our object and lower values indicate increased complexity, irregularity, or elongation of the shape.

Schumm’s Elongation Ratio (1956) was developed to describe the elongation of drainage basins in New Jersey. It is defined as the ratio of the diameter of a circle with the same area as the object to the object’s major axis length such that: . Where *A* is the area of the object and *L1* is the length of the major axis of the ellipse. In this case, a perfectly circular atoll or object equals 1 and as the object becomes more elongated in shape the value decreases to zero.

Lastly, we investigated Stoddart’s (1965) Ellipticity index developed to describe the elliptical form of atolls. It is defined as the ratio of the major axis of the ellipse with the same area as the atoll to the minor axis of the ellipse with the same area as the atoll such that: . Where *A* is the area of the object and *L1* is the length of the major axis of the ellipse with the same area as the atoll. This index corresponds to 1 for a perfectly circular atoll and increases in value for more elliptical shapes.

In addition to the 4 shape factors detailed above (Figure 8), our code also provides the majority of the shape factors calculated in the new GIS plugin – PolyMorph-2D (2021). These values are saved for each object in the csv files. We find that for Stoddart’s shape factors are an easy method to assess the circularity, complexity, and ellipticity of each atoll and object in our database.

# Error Propagation and Statistical Analysis

A range of statistical analysis is performed on our database including non-parametric variance analysis (Kruskal-Wallis & post-hoc Dunn Test) as well as error propagation of our measurements. To correctly propagate the error of a mean of mean values of varying sample size, the following equation is used:

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Where *n* is the sample size of each mean population, is the variance of each population, and *N* is the total number of populations averaged over. For example, if we wanted to calculate the mean motu width on Faaite, we would take the mean of the mean motu width of each of the seven motu (Figure 3). We would then calculate the standard deviation of this mean motu width for Faaite Atoll by taking the calculated standard deviation of each motu () and the sample size of points used to calculate each motu width (*n*) in the above equation to correctly propagate the error associated with this calculation where *N* = 7.

The following Tables (Tables S2-S9) contain in the last column the outputted p-values assuming an alpha = 0.05 from the Kruskal-Wallis non-parametric analysis of variance on our databases when comparing the different groupings of our data (i.e. grouping motu morphometrics by cardinal position on an atoll within French Polynesia or grouping reef-flats by absolute latitude). For each analysis, we then provide the results from the post-hoc Dunn Test to differentiate each group from each other with the outputted p-values (again assuming an alpha = 0.05) shown. Each statistical analysis is linked to a figure or table in the main text, allowing us to statistically differentiate our different populations of morphometrics.

# Figures

Diagram

Description automatically generated

Figure S1. Example of per-perimeter point morphometrics of width on Faaite Atoll, French Polynesia for a) motu width (black lines), b) ocean side reef width (red lines), lagoon side reef width (white lines), c) total reef flat width (purple lines), and d) effective reef flat width (blue lines). The motu are yellow, reef flat are teal, and water is purple. The atoll centroid and crossed dashed grey lines show how points are binned by cardinal position on the atoll (North, East, South and West).

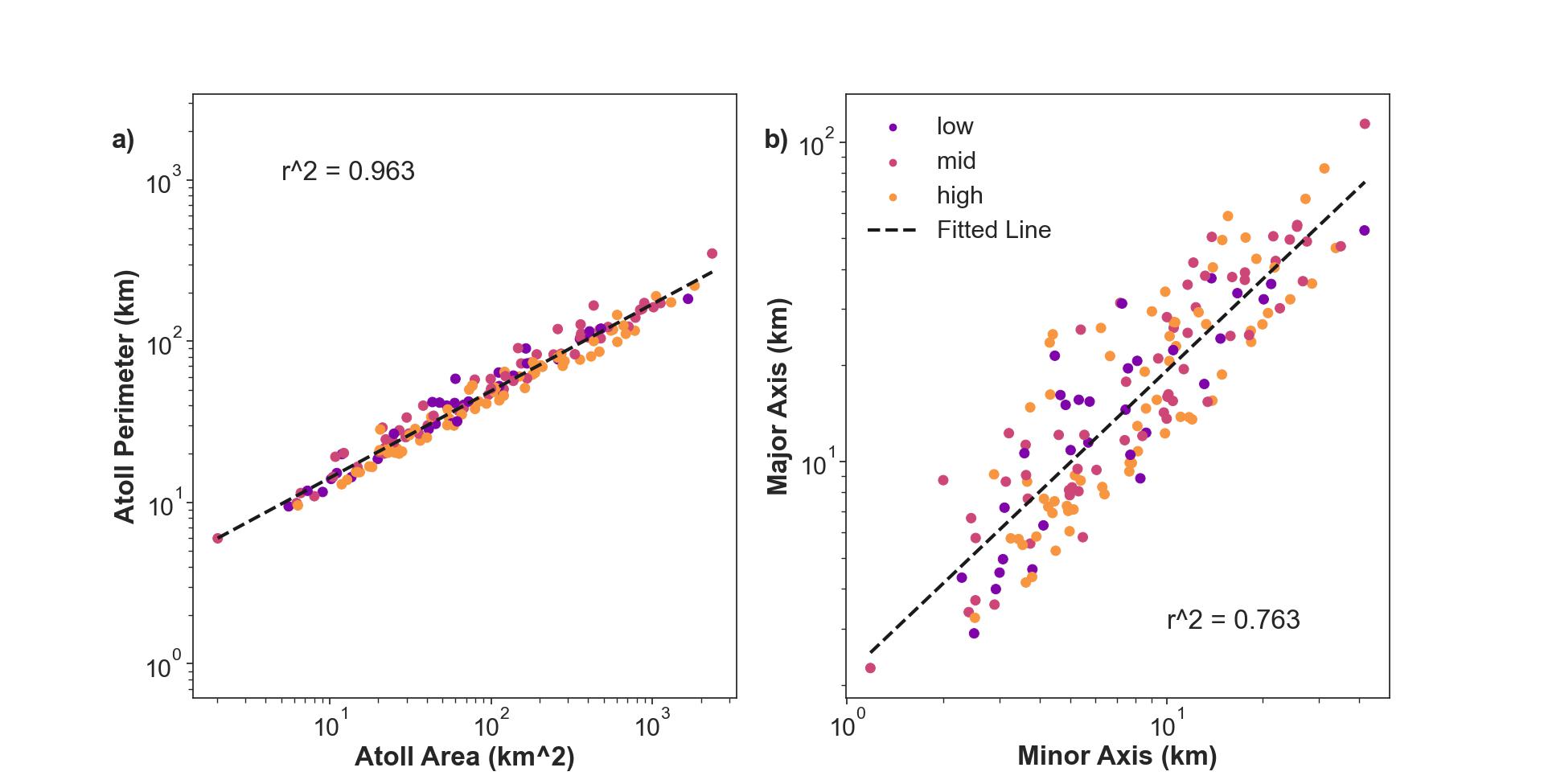


Figure S2. a) Logscale plot of entire atoll area (km) vs atoll perimeter (km) grouped by latitude with a best fit least squares regression (black dashed line). b) Logscale plot of the length of the minor vs major axis of the ellipse with the same normalized second central moments as the atoll grouped by latitude with a best fit least squares regression line shown (black dashed line).

# Tables

Table S1: Summary of all 154 Atolls analyzed with total area for each landcover class listed

| Ocean Basin | Country | Name | Location | # Motu | # Reef Flat | Land Area (km2) | Lagoon Area (km2) | Reef Flat Area (km2) | % Reef Flat Length Blocked |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Indian | India | Bangaram | 10.94°N, 72.29°E | 2/4 | 2 | 1.23 | 5.84 | 23.43 | 8.5 |
| Kalpeni | 10.1°N, 73.64°E | 2/7 | 3 | 3.2 | 4.48 | 21.36 | 38.7 |
| Minicoy | 8.28°N, 73.03°E | 1/3 | 2 | 4.98 | 12.78 | 16 | 46.7 |
| Republic of Maldives | Goidhoo | 4.86°N, 72.9°E | 4/6 | 3 | 2.28 | 69.48 | 29.89 | 10.3 |
| Kaashidhoo | 4.96°N, 73.46°E | 1/3 | 2 | 2.84 | 1.58 | 6.21 | 38.7 |
| Kolhumadulu | 2.55°N, 73.07°E | 27/53 | 23 | 10.11 | 1533.24 | 124.21 | 20.8 |
| Rasdhoo | 4.3°N, 72.96°E | 3/5 | 5 | 0.65 | 41.29 | 15.22 | 13.2 |
| Seychelles | Aldabra | 9.42°S, 46.35°E | 10/44 | 8 | 153.9 | 13.64 | 338.54 | 38 |
| United Kingdom | Diego Garcia | 7.23°S, 72.42°E | 2/5 | 4 | 30.9 | 112.25 | 63.37 | 85.5 |
| Peros Banhos | 5.24°S, 71.83°E | 20/27 | 12 | 8.75 | 438.27 | 38.44 | 48.9 |
| Saloman | 5.34°S, 72.24°E | 5/10 | 1 | 3.22 | 21.69 | 13.84 | 48.3 |
| Pacific | Caroline Islands | Ant | 6.79°N, 157.95°E | 7/12 | 1 | 3.04 | 70.61 | 25.46 | 34.3 |
| Ifalik | 7.25°N, 144.45°E | 2/2 | 1 | 1.42 | 2.06 | 4.46 | 44.2 |
| Murilo | 8.75°N, 152.3°E | 5/12 | 10 | 1.47 | 368.86 | 30.92 | 7.6 |
| Namoluk | 5.92°N, 153.14°E | 3/7 | 1 | 1.7 | 7.3 | 7.42 | 41.7 |
| Nomwin | 8.6°N, 151.79°E | 4/10 | 11 | 1.6 | 290.93 | 38.94 | 9.3 |
| Pakin | 7.06°N, 157.8°E | 8/15 | 1 | 2.68 | 11.14 | 13.79 | 46.9 |
| Ulithi | 10.07°N, 139.73°E | 15/33 | 23 | 4.24 | 310.2 | 46.04 | 19.2 |
| Woleai | 7.37°N, 143.91°E | 9/16 | 5 | 4.26 | 27.57 | 15.46 | 53.8 |
| Fiji | Fulqana | 19.14°S, 178.57°W | 8/20 | 1 | 18.29 | 15.33 | 48.48 | 57.4 |
| Nggelelevu | 16.09°S, 179.25°W | 2/3 | 5 | 1.67 | 123.49 | 61.54 | 6.3 |
| Wailangilala | 16.77°S, 179.1°W | 2/2 | 1 | 0.48 | 11.57 | 10.68 | 10.1 |
| France | Beautemps Beaupre | 20.33°S, 166.18°E | 1/2 | 4 | 0.55 | 53 | 62.04 | 5.4 |
| Nokanhui | 22.73°S, 167.57°E | 2/2 | 3 | 0.63 | 2.77 | 16.34 | 6.8 |
| Ouvea | 20.55°S, 166.55°E | 22/35 | 33 | 156.88 | 683.37 | 364.52 | 60.8 |
| French Polynesia | Ahe | 14.49°S, 146.32°W | 21/26 | 1 | 18.16 | 147.85 | 32.28 | 97.6 |
| Amanu | 17.81°S, 140.76°W | 24/62 | 2 | 17.51 | 219.59 | 39.14 | 82 |
| Apataki | 15.46°S, 146.29°W | 25/70 | 2 | 28.99 | 706.65 | 72.02 | 69.4 |
| Aratika | 15.48°S, 145.51°W | 17/48 | 2 | 13.15 | 154.66 | 32.65 | 73 |
| Arutua | 15.32°S, 146.76°W | 26/54 | 1 | 19.51 | 535.7 | 71.5 | 55.2 |
| Faaite | 16.76°S, 145.24°W | 7/27 | 2 | 11.48 | 233.37 | 52.27 | 52.6 |
| Fakahina | 15.99°S, 140.13°W | 1/1 | 1 | 11.88 | 18.31 | 18.04 | 100 |
| Fakarava | 16.29°S, 145.51°W | 22/71 | 2 | 27.22 | 1157.47 | 149.2 | 53.6 |
| Fangatau | 15.82°S, 140.87°W | 3/5 | 1 | 9.53 | 8.06 | 14.86 | 96.4 |
| Fangataufa | 22.24°S, 138.75°W | 9/25 | 1 | 5.62 | 39.03 | 15.68 | 80.2 |
| Hao | 18.26°S, 140.88°W | 73/183 | 1 | 33 | 520.38 | 84.48 | 83.6 |
| Haraiki | 17.47°S, 143.45°W | 4/12 | 1 | 5.12 | 10.77 | 15.14 | 61.4 |
| Pacific | French Polynesia | Hikueru | 17.59°S, 142.61°W | 4/13 | 1 | 6.4 | 81.45 | 30.96 | 47.7 |
| Hiti | 16.73°S, 144.1°W | 1/4 | 1 | 3.09 | 14.4 | 12.55 | 55.2 |
| Katiu | 16.36°S, 144.42°W | 11/44 | 2 | 12.03 | 238.59 | 39.52 | 61.1 |
| Kauehi | 15.87°S, 145.14°W | 14/44 | 1 | 18.54 | 319.31 | 36.66 | 78.5 |
| Kaukura | 15.76°S, 146.71°W | 33/72 | 3 | 17.55 | 431.01 | 138.62 | 37.7 |
| Manihi | 14.4°S, 145.95°W | 20/38 | 1 | 19.42 | 169.11 | 33.89 | 93.1 |
| Manuhangi | 19.2°S, 141.25°W | 1/2 | 1 | 3.92 | 8.62 | 6.72 | 95 |
| Maria Est | 22.02°S, 136.19°W | 2/2 | 1 | 4.19 | 6.81 | 7.7 | 98.1 |
| Marokau | 18.06°S, 142.29°W | 16/30 | 1 | 15.83 | 224.65 | 46.94 | 67.1 |
| Marutea Nord | 17.07°S, 143.16°W | 12/31 | 1 | 7.53 | 468.39 | 83.8 | 29.7 |
| Marutea Sud | 21.52°S, 135.56°W | 23/59 | 1 | 12.17 | 117.6 | 31.96 | 73.5 |
| Matureivavao | 21.47°S, 136.4°W | 1/4 | 1 | 4.38 | 18.29 | 9.8 | 84.7 |
| Maupihaa | 16.82°S, 153.96°W | 3/9 | 1 | 4.87 | 30 | 23.3 | 38.7 |
| Moruoa | 21.85°S, 138.91°W | 14/48 | 2 | 10.32 | 146.92 | 33.92 | 60.2 |
| Motu One | 15.82°S, 154.53°W | 4/4 | 1 | 3.84 | 2.74 | 10.05 | 78.5 |
| Motutunga | 17.12°S, 144.37°W | 20/43 | 2 | 4.87 | 127.3 | 34.91 | 50 |
| Nengonengo | 18.76°S, 141.82°W | 7/17 | 1 | 7.67 | 70.71 | 22.89 | 72.1 |
| Niau | 16.16°S, 146.35°W | 1/1 | 1 | 21.51 | 33.91 | 25.01 | 113.9 |
| Nihiru | 16.7°S, 142.83°W | 12/29 | 1 | 9.94 | 77.42 | 27.54 | 75.3 |
| Paraoa | 19.14°S, 140.69°W | 2/7 | 1 | 4.51 | 16.45 | 8.96 | 87.8 |
| Pukarua | 18.32°S, 137.02°W | 4/6 | 1 | 12.96 | 30.45 | 23.4 | 101.8 |
| Rangiroa | 15.17°S, 147.59°W | 69/184 | 4 | 73.38 | 1630.56 | 196.9 | 76.4 |
| Raraka | 16.19°S, 144.9°W | 28/70 | 1 | 18.42 | 369.85 | 47.4 | 81.4 |
| Raroia | 16.09°S, 142.42°W | 50/114 | 1 | 23.08 | 371.8 | 61.4 | 77.1 |
| Ravahere | 18.24°S, 142.16°W | 6/20 | 1 | 9.16 | 46.33 | 29.88 | 62.7 |
| Reao | 18.52°S, 136.38°W | 6/6 | 2 | 21.64 | 41.19 | 35.5 | 102 |
| Reitoru | 17.86°S, 143.08°W | 3/3 | 1 | 2.48 | 5.02 | 9.75 | 63 |
| Scilly | 16.55°S, 154.69°W | 5/10 | 1 | 5.77 | 84.92 | 35.08 | 43.4 |
| Taenga | 16.36°S, 143.13°W | 11/53 | 1 | 12.5 | 174.44 | 33.82 | 60.1 |
| Tahanea | 16.9°S, 144.79°W | 30/69 | 3 | 15.11 | 561.66 | 100.93 | 52 |
| Taiaro | 15.74°S, 144.63°W | 2/3 | 1 | 3.09 | 12.41 | 5.15 | 86 |
| Takapoto | 14.63°S, 145.21°W | 2/3 | 1 | 16.62 | 79.73 | 27.01 | 102 |
| Takaroa | 14.45°S, 144.96°W | 10/13 | 1 | 19.52 | 89.6 | 31.57 | 98.8 |
| Takume | 15.79°S, 142.19°W | 32/49 | 1 | 11.91 | 42.3 | 30.82 | 81.1 |
| Tatakoto | 17.34°S, 138.39°W | 14/20 | 1 | 12.31 | 18.29 | 23.88 | 83.1 |
| Tauere | 17.38°S, 141.51°W | 3/8 | 1 | 4.72 | 7.99 | 10.33 | 87.8 |
| Tematangi | 21.68°S, 140.63°W | 13/14 | 1 | 10.02 | 64.33 | 19.54 | 98.3 |
| Temoe | 23.35°S, 134.48°W | 9/16 | 1 | 3.8 | 14.46 | 8.78 | 87.4 |
| Tepoto Sud | 16.82°S, 144.28°W | 3/3 | 1 | 2.77 | 1.25 | 5.08 | 103.6 |
| Pacific | French Polynesia | Tetiaroa | 17.01°S, 149.56°W | 6/9 | 1 | 5.55 | 9.67 | 23.76 | 37.2 |
| Tikehau | 15.02°S, 148.17°W | 48/86 | 2 | 32.81 | 399.62 | 70.06 | 95.9 |
| Toau | 15.93°S, 146.05°W | 20/31 | 4 | 15.94 | 570.45 | 113.38 | 48.5 |
| Tuanake | 16.66°S, 144.22°W | 9/27 | 1 | 5.61 | 25.55 | 14.41 | 73.4 |
| Tupai | 16.27°S, 151.82°W | 4/4 | 1 | 11.25 | 6.91 | 23.75 | 57.7 |
| Tureia | 20.83°S, 138.54°W | 2/2 | 1 | 10.56 | 61.9 | 17.63 | 99.7 |
| Vahanga | 21.33°S, 136.65°W | 1/1 | 1 | 3.78 | 5.26 | 6.59 | 98.1 |
| Vahitahi | 18.78°S, 138.83°W | 9/13 | 1 | 5.21 | 8.3 | 12.02 | 76.3 |
| Vairaatea | 19.35°S, 139.23°W | 5/8 | 1 | 4.82 | 13.5 | 9.44 | 87.4 |
| Indonesia | Dauwi | 1.27°S, 136.68°E | 4/4 | 6 | 2.07 | 10.65 | 8.67 | 27.5 |
| Kakaban | 2.14°N, 118.54°E | 1/1 | 1 | 6.03 | 4.45 | 7.29 | 105.4 |
| Mapia | 0.88°N, 134.31°E | 3/4 | 1 | 3.21 | 23.63 | 35.51 | 25.1 |
| Maratua | 2.19°N, 118.65°E | 3/12 | 9 | 23.19 | 43.48 | 115.27 | 27.2 |
| Nggasuang | 2.19°S, 123.44°E | 3/5 | 3 | 1.02 | 31.2 | 38.14 | 6 |
| Noekori | 0.9°S, 135.45°E | 3/3 | 1 | 3.68 | 7.49 | 50.08 | 11.9 |
| Pulau Karompa Lompa | 7.23°S, 121.61°E | 2/3 | 17 | 13.79 | 139.31 | 108.28 | 6.2 |
| Pulau Kokota | 0.62°S, 128.54°E | 18/39 | 1 | 8.91 | 12.67 | 33.97 | 56.2 |
| Pulau Lentea | 5.81°S, 123.89°E | 2/2 | 11 | 8.5 | 32.33 | 44.03 | 15.4 |
| Pulau Panggang | 5.74°S, 106.6°E | 1/1 | 1 | 0.15 | 0.46 | 1.52 | 10.9 |
| Pulau Pei | 1.24°S, 136.38°E | 5/8 | 1 | 14.05 | 66.46 | 66.75 | 27.6 |
| Pulau Sapuka | 7.07°S, 118.15°E | 1/1 | 3 | 1.17 | 4.7 | 30.84 | 6.6 |
| Pulau Sukar | 0.56°S, 128.39°E | 9/21 | 1 | 15.35 | 7.08 | 35.94 | 74.4 |
| Pulau Urbabo | 0.39°N, 130.99°E | 2/4 | 3 | 5.89 | 22.08 | 87.55 | 10.1 |
| Sabalana | 6.84°S, 119.12°E | 10/26 | 15 | 9.83 | 54.26 | 82.97 | 8.2 |
| Tiger | 5.86°S, 106.6°E | 2/7 | 1 | 0.92 | 1.45 | 8.94 | 13.1 |
| Kiribati | Abaiang | 1.88°N, 172.91°E | 9/25 | 12 | 17.99 | 249.43 | 103.01 | 50.2 |
| Abemama | 0.41°N, 173.88°E | 5/7 | 4 | 31.89 | 151.29 | 108.47 | 71.4 |
| Aranuka | 0.17°N, 173.6°E | 4/12 | 2 | 16.07 | 17.35 | 49.38 | 68.5 |
| Beru | 1.32°S, 175.98°E | 1/9 | 1 | 18.37 | 0.78 | 51.01 | 52.8 |
| Butaritari | 3.18°N, 172.83°E | 16/69 | 6 | 23.23 | 290.74 | 114.32 | 45.6 |
| Maiana | 0.94°N, 173°E | 7/14 | 5 | 26.04 | 46.24 | 116.78 | 41.6 |
| Marakei | 2.01°N, 173.28°E | 1/10 | 1 | 13.61 | 17.02 | 27.91 | 96.4 |
| Onotoa | 1.87°S, 175.57°E | 2/5 | 10 | 13.85 | 29.32 | 79.28 | 55.7 |
| Orona | 4.51°S, 172.18°W | 3/4 | 1 | 8.02 | 24.69 | 15.96 | 93.1 |
| Tarawa | 1.48°N, 173.02°E | 18/34 | 2 | 36.3 | 342.93 | 133.55 | 63 |
| Marshall Islands | Ailinginae | 11.15°N, 166.41°E | 18/34 | 2 | 5.71 | 105 | 48.56 | 34.5 |
| Ailinglapalap | 7.57°N, 168.93°E | 26/42 | 15 | 16.23 | 768.26 | 70.24 | 51.8 |
| Ailuk | 10.35°N, 169.96°E | 36/49 | 4 | 11.33 | 188.51 | 55.42 | 42.6 |
| Pacific | Marshall Islands | Arno | 7.11°N, 171.69°E | 43/90 | 7 | 20.84 | 350.51 | 81.34 | 65.8 |
| Aur | 8.25°N, 171.13°E | 16/47 | 5 | 7.01 | 234.05 | 38.18 | 29 |
| Bikar | 12.25°N, 170.11°E | 3/6 | 1 | 0.57 | 40.05 | 22.06 | 7.2 |
| Bikini | 11.65°N, 165.38°E | 15/23 | 8 | 8.35 | 615.65 | 93.63 | 23.9 |
| Jaluit | 6.13°N, 169.47°E | 35/56 | 9 | 20.41 | 781.05 | 106.91 | 59.2 |
| Knox | 5.91°N, 172.15°E | 10/16 | 1 | 2.8 | 1.05 | 11.12 | 83.6 |
| Kwajalein | 9.32°N, 167.52°E | 57/97 | 41 | 22.04 | 2214.77 | 127.49 | 36.7 |
| Likiep | 9.95°N, 169.16°E | 39/75 | 8 | 13.39 | 411.88 | 58.81 | 44.9 |
| Majuro | 7.13°N, 171.17°E | 20/54 | 7 | 16.31 | 306.84 | 50.43 | 75.8 |
| Maloelap | 8.76°N, 171.08°E | 29/84 | 14 | 11.94 | 939.05 | 77.44 | 27.1 |
| Millie | 6.25°N, 171.92°E | 48/87 | 11 | 22.51 | 773.99 | 91.64 | 74.1 |
| Rongelap | 11.45°N, 166.95°E | 35/64 | 9 | 11.78 | 1006.62 | 115.38 | 31.6 |
| Taka | 11.17°N, 169.63°E | 4/6 | 4 | 0.85 | 99.6 | 37.49 | 6.3 |
| Ujelang | 9.83°N, 160.9°E | 15/39 | 4 | 3.84 | 68.82 | 30.33 | 26.6 |
| Utirik | 11.27°N, 169.8°E | 4/7 | 4 | 3.56 | 68.88 | 30.32 | 21.7 |
| Wotho | 10.12°N, 165.99°E | 9/19 | 8 | 6.03 | 90 | 31.97 | 27.9 |
| Wotje | 9.5°N, 170.07°E | 36/61 | 11 | 14.34 | 706.98 | 76.99 | 36.1 |
| New Zealand | Fakaofo | 9.38°S, 171.22°W | 10/32 | 2 | 4.03 | 47.39 | 20.1 | 41.2 |
| Nikunonu | 9.16°S, 171.82°W | 11/33 | 1 | 4.53 | 97.21 | 21.48 | 49.1 |
| Papua New Guinea | Awin | 1.65°S, 144.02°E | 2/2 | 1 | 0.84 | 3.43 | 5.58 | 29.9 |
| Budibudi | 9.29°S, 153.67°E | 4/7 | 2 | 3.23 | 9.15 | 12.38 | 52.6 |
| Conflict | 10.73°S, 151.8°E | 10/18 | 7 | 4.18 | 156.08 | 34.91 | 31 |
| Duperre | 11.19°S, 151.94°E | 4/5 | 5 | 0.85 | 116.01 | 50.36 | 5 |
| Heina | 1.12°S, 144.5°E | 7/7 | 2 | 2.87 | 5.9 | 7.54 | 61.9 |
| Liot | 1.41°S, 144.51°E | 1/1 | 1 | 1.23 | 1.26 | 4.27 | 42.6 |
| Ninigo | 1.23°S, 144.34°E | 12/15 | 9 | 7.57 | 324.78 | 82.58 | 18.6 |
| Palawat | 1.95°S, 146.49°E | 1/4 | 2 | 0.14 | 6.62 | 3.08 | 6.7 |
| Pelleluhu | 1.13°S, 144.39°E | 10/11 | 1 | 5.52 | 29.09 | 31.98 | 37.1 |
| Pinipel | 4.4°S, 154.13°E | 1/2 | 1 | 6.02 | 7.79 | 16.75 | 54.4 |
| Sama | 1.4°S, 144.08°E | 2/3 | 1 | 0.7 | 1.31 | 5.93 | 26.5 |
| Samasuma | 1.47°S, 144.04°E | 1/2 | 1 | 2.25 | 2.89 | 7.9 | 40.1 |
| Philippines | Sibutu Group | 4.73°N, 119.37°E | 10/15 | 11 | 27.79 | 107.65 | 396.41 | 10.6 |
| The Republic of Palau | Kayangel | 8.07°N, 134.7°E | 3/4 | 1 | 1.67 | 2.43 | 18.92 | 22.1 |
| Tuvalu | Nanumea | 5.67°S, 176.1°E | 2/5 | 1 | 4.04 | 3.34 | 17.51 | 43.3 |
| Nui | 7.22°S, 177.15°E | 5/9 | 1 | 6.1 | 2.7 | 17.28 | 69.4 |
| Nukufetau | 8°S, 178.37°E | 8/35 | 2 | 5.48 | 93.01 | 26.1 | 51.7 |
| Nukulaelae | 9.39°S, 179.84°E | 8/19 | 1 | 3.53 | 16.73 | 23.19 | 54.1 |
| Vaitupu | 7.48°S, 178.68°E | 1/4 | 1 | 5.79 | 0.56 | 9.55 | 78.5 |
| Pacific | United Kingdom | Nukapu | 10.09°S, 166.04°E | 1/1 | 1 | 0.35 | 0.26 | 5.87 | 15.7 |
|  | Nupani | 10.07°S, 165.72°E | 1/4 | 1 | 0.38 | 9.36 | 12.73 | 6.5 |
| **Total** | **17** | **154** | **1,752/3,786** | | **593** | **1,831.6** | **27,784** | **7,370.4** |  |

Table S2. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis of cardinal position binned per atoll in French Polynesia Atolls (n = 60 atolls, 231 data points) paired with Figure 5 and 6.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Variable Tested |  | North | East | South | West | kruskal wallis p-value |
| Mean Reef Flat Width (m) | **North** | 1.000 | 0.029 | < 0.001 | < 0.001 | < 0.001 |
| **East** | 0.029 | 1.000 | 0.004 | 0.005 |
| **South** | < 0.001 | 0.004 | 1.000 | 1.000 |
| **West** | < 0.001 | 0.005 | 1.000 | 1.000 |
| Mean Ocean Reef Width (m) | **North** | 1.000 | 1.000 | < 0.001 | < 0.001 | < 0.001 |
| **East** | 1.000 | 1.000 | < 0.001 | < 0.001 |
| **South** | < 0.001 | < 0.001 | 1.000 | 0.591 |
| **West** | < 0.001 | < 0.001 | 0.591 | 1.000 |
| Mean Motu Width (m) | **North** | 1.000 | 1.000 | 0.125 | 0.404 | < 0.001 |
| **East** | 1.000 | 1.000 | 0.114 | 0.437 |
| **South** | 0.125 | 0.114 | 1.000 | < 0.001 |
| **West** | 0.404 | 0.437 | < 0.001 | 1.000 |
| Mean Effective Reef Flat Width (m) | **North** | 1.000 | 0.008 | 0.000 | 0.000 | < 0.001 |
| **East** | 0.008 | 1.000 | 0.000 | 0.011 |
| **South** | < 0.001 | 0.000 | 1.000 | 0.578 |
| **West** | < 0.001 | 0.011 | 0.578 | 1.000 |
| Sum Motu Length (m) | **North** | 1.000 | 1.000 | 0.000 | 0.982 | < 0.001 |
| **East** | 1.000 | 1.000 | 0.000 | 0.296 |
| **South** | < 0.001 | 0.000 | 1.000 | 0.014 |
| **West** | 0.982 | 0.296 | 0.014 | 1.000 |
| Mean % Sum Reef Flat Blocked | **North** | 1.000 | 0.120 | < 0.001 | < 0.001 | < 0.001 |
| **East** | 0.120 | 1.000 | < 0.001 | 0.003 |
| **South** | < 0.001 | < 0.001 | 1.000 | 0.333 |
| **West** | < 0.001 | 0.003 | 0.333 | 1.000 |

Table S3. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for cardinal binning for French Polynesia binned per atoll (n = 231-836) paired with Figure 7.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **VARIABLE TESTED** |  | **NORTH** | **EAST** | **SOUTH** | **WEST** | **KRUSKAL WALLIS P-VALUE** |
| **Per Atoll Cardinal Mean Ocean Reef Width (m)** | **North** | 1.000 | 1.000 | < 0.001 | < 0.001 | < 0.001 |
| **East** | 1.000 | 1.000 | < 0.001 | < 0.001 |
| **South** | < 0.001 | < 0.001 | 1.000 | 0.591 |
| **West** | < 0.001 | < 0.001 | 0.591 | 1.000 |
| **Per Atoll Cardinal Mean Motu Length (m)** | **North** | 1.000 | 1.000 | < 0.001 | 0.982 | < 0.001 |
| **East** | 1.000 | 1.000 | < 0.001 | 0.296 |
| **South** | < 0.001 | < 0.001 | 1.000 | 0.014 |
| **West** | 0.982 | 0.296 | 0.014 | 1.000 |
| **Per Object Cardinal Mean Ocean Reef Width (m)** | **North** | 1.000 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| **East** | < 0.001 | 1.000 | < 0.001 | 0.932 |
| **South** | < 0.001 | < 0.001 | 1.000 | 0.009 |
| **West** | < 0.001 | 0.932 | 0.009 | 1.000 |
| **Per Object Cardinal Motu Length (m)** | **North** | 1.000 | 0.159 | < 0.001 | < 0.001 | < 0.001 |
| **East** | 0.159 | 1.000 | < 0.001 | 0.039 |
| **South** | < 0.001 | < 0.001 | 1.000 | 0.720 |
| **West** | < 0.001 | 0.039 | 0.720 | 1.000 |
| **Per Object Normalized Cardinal motu length/reef flat length** | **North** | 1.000 | 0.022 | < 0.001 | < 0.001 | < 0.001 |
| **East** | 0.022 | 1.000 | 0.002 | 0.923 |
| **South** | < 0.001 | 0.002 | 1.000 | 0.105 |
| **West** | < 0.001 | 0.923 | 0.105 | 1.000 |
| **Per Object Normalized Cardinal motu ocean reef/reef flat width** | **North** | 1.000 | 0.001 | < 0.001 | 0.007 | < 0.001 |
| **East** | 0.001 | 1.000 | 0.713 | 1.000 |
| **South** | < 0.001 | 0.713 | 1.000 | 0.038 |
| **West** | 0.007 | 1.000 | 0.038 | 1.000 |

Table S4. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for latitude regional analysis per point (n = 181,448-416,685) paired with Table 2.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable Tested** |  | **EQUATORIAL** | **MID-TROPICAL** | **HIGH-TROPICAL** | **KRUSKAL WALLIS P-VALUE** |
| **Per Atoll # all motu** | **Equatorial** | 1.000 | 0.122 | 0.048 | 0.046 |
| **Mid-Tropical** | 0.122 | 1.000 | 1.000 |
| **High-Tropical** | 0.048 | 1.000 | 1.000 |
| **Per Atoll # small motu** | **Equatorial** | 1.000 | 0.298 | 0.034 | 0.011 |
| **Mid-Tropical** | 0.298 | 1.000 | 0.828 |
| **High-Tropical** | 0.034 | 0.828 | 1.000 |
| **Per Atoll # large motu** | **Equatorial** | 1.000 | 0.117 | 0.025 | 0.029 |
| **Mid-Tropical** | 0.117 | 1.000 | 1.000 |
| **High-Tropical** | 0.025 | 1.000 | 1.000 |
| **Per Atoll # reef flat** | **Equatorial** | 1.000 | 0.124 | 0.029 | < 0.001 |
| **Mid-Tropical** | 0.124 | 1.000 | < 0.001 |
| **High-Tropical** | 0.029 | < 0.001 | 1.000 |
| **Per Atoll Total Reef Flat Area** | **Equatorial** | 1.000 | 1.000 | 1.000 | 0.621 |
| **Mid-Tropical** | 1.000 | 1.000 | 1.000 |
| **High-Tropical** | 1.000 | 1.000 | 1.000 |
| **Per Atoll mean reef flat area** | **Equatorial** | 1.000 | 0.022 | 0.119 | < 0.001 |
| **Mid-Tropical** | 0.022 | 1.000 | < 0.001 |
| **High-Tropical** | 0.119 | < 0.001 | 1.000 |
| **Per Atoll Total motu area** | **Equatorial** | 1.000 | 0.339 | 0.692 | 0.003 |
| **Mid-Tropical** | 0.339 | 1.000 | 0.002 |
| **High-Tropical** | 0.692 | 0.002 | 1.000 |
| **Per Atoll mean motu area** | **Equatorial** | 1.000 | 0.001 | 1.000 | < 0.001 |
| **Mid-Tropical** | 0.001 | 1.000 | < 0.001 |
| **High-Tropical** | 1.000 | < 0.001 | 1.000 |
| **Per Atoll total motu length** | **Equatorial** | 1.000 | 1.000 | 0.006 | < 0.001 |
| **Mid-Tropical** | 1.000 | 1.000 | 0.002 |
| **High-Tropical** | 0.006 | 0.002 | 1.000 |
| **Per Atoll mean motu length** | **Equatorial** | 1.000 | 0.054 | 1.000 | < 0.001 |
| **Mid-Tropical** | 0.054 | 1.000 | < 0.001 |
| **High-Tropical** | 1.000 | < 0.001 | 1.000 |

Table S5. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for per atoll analysis binned by latitude (n = 154) paired with Figure 8.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable Tested** |  | **Equatorial** | **Mid Tropical** | **High Tropical** | **Kruskal Wallis p-value** |
| **Horton Form Factor** | **Equatorial** | 1.000 | 1.000 | 0.380 | 0.028 |
| **Mid-Tropical** | 1.000 | 1.000 | 0.027 |
| **High-Tropical** | 0.380 | 0.027 | 1.000 |
| **Miller Circularity Ratio** | **Equatorial** | 1.000 | 0.993 | 0.013 | < 0.001 |
| **Mid-Tropical** | 0.993 | 1.000 | < 0.001 |
| **High-Tropical** | 0.013 | < 0.001 | 1.000 |
| **Schumm’s Elongation Ratio** | **Equatorial** | 1.000 | 1.000 | 0.377 | 0.029 |
| **Mid-Tropical** | 1.000 | 1.000 | 0.028 |
| **High-Tropical** | 0.377 | 0.028 | 1.000 |
| **Ellipticity Index** | **Equatorial** | 1.000 | 1.000 | 1.000 | 0.058 |
| **Mid-Tropical** | 1.000 | 1.000 | 1.000 |
| **High-Tropical** | 1.000 | 1.000 | 1.000 |

Table S6. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for latitude regional analysis per point (n = 181,448-416,685) paired with Figure 9.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable Tested** |  | **EQUATORIAL** | **MID-TROPICAL** | **HIGH-TROPICAL** | **KRUSKAL WALLIS P-VALUE** |
| **Reef Flat Width (m)** | **Equatorial** | 1 | 0 | 0 | < 0.001 |
| **Mid-Tropical** | 0 | 1 | < 0.001 |
| **High-Tropical** | 0 | < 0.001 | 1 |
| **Ocean Reef Width (m)** | **Equatorial** | 1 | < 0.001 | 0 | < 0.001 |
| **Mid-Tropical** | < 0.001 | 1 | < 0.001 |
| **High-Tropical** | 0 | < 0.001 | 1 |
| **Motu width (m)** | **Equatorial** | 1 | 0 | < 0.001 | < 0.001 |
| **Mid-Tropical** | 0 | 1 | < 0.001 |
| **High-Tropical** | < 0.001 | < 0.001 | 1 |
| **Lagoon Reef Width (m)** | **Equatorial** | 1 | < 0.001 | 0 | < 0.001 |
| **Mid-Tropical** | < 0.001 | 1 | 0 |
| **High-Tropical** | 0 | 0 | 1 |
| **Effective Reef Flat Width (m)** | **Equatorial** | 1 | < 0.001 | 0 | < 0.001 |
| **Mid-Tropical** | < 0.001 | 1 | 0 |
| **High-Tropical** | 0 | 0 | 1 |

Table S7. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for latitude regional analysis binned per motu (n = 1,753) paired with Figure 10.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **VARIABLE TESTED** |  | **Equatorial** | **Mid-Tropical** | **High-Tropical** | **KRUSKAL WALLIS P-VALUE** |
| **Motu Area (M2)** | **Equatorial** | 1.000 | 0.016 | 0.013 | 0.012 |
| **Mid-Tropical** | 0.016 | 1.000 | 1.000 |
| **High-Tropical** | 0.013 | 1.000 | 1.000 |
| **Motu Width (M)** | **Equatorial** | 1.000 | 0.004 | 0.012 | 0.005 |
| **Mid-Tropical** | 0.004 | 1.000 | 1.000 |
| **High-Tropical** | 0.012 | 1.000 | 1.000 |
| **Motu Length (M)** | **Equatorial** | 1.000 | 0.136 | 0.004 | 0.004 |
| **Mid-Tropical** | 0.136 | 1.000 | 0.194 |
| **High-Tropical** | 0.004 | 0.194 | 1.000 |

Table S8. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for latitude regional analysis binned per motu (n = 1,749) paired with Figure 12.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable Tested** |  | **EQUATORIAL** | **MID-TROPICAL** | **HIGH-TROPICAL** | **KRUSKAL WALLIS P-VALUE** |
| **Per Motu Mean Ocean Reef Width (m)** | **Equatorial** | 1.000 | < 0.001 | < 0.001 | < 0.001 |
| **Mid-Tropical** | < 0.001 | 1.000 | 0.008 |
| **High-Tropical** | < 0.001 | 0.008 | 1.000 |
| **Per Motu Mean Motu Length (m)** | **Equatorial** | 1.000 | 0.136 | 0.004 | 0.004 |
| **Mid-Tropical** | 0.136 | 1.000 | 0.194 |
| **High-Tropical** | 0.004 | 0.194 | 1.000 |
| **Per Object Normalized motu length/reef flat length** | **Equatorial** | 1.000 | 1.000 | < 0.001 | < 0.001 |
| **Mid-Tropical** | 1.000 | 1.000 | < 0.001 |
| **High-Tropical** | < 0.001 | < 0.001 | 1.000 |
| **Per Object Normalized motu ocean reef/reef flat width** | **Equatorial** | 1.000 | 1.000 | 1.000 | 0.177 |
| **Mid-Tropical** | 1.000 | 1.000 | 1.000 |
| **High-Tropical** | 1.000 | 1.000 | 1.000 |
| **> 1 km Per Motu Mean Ocean Reef Width (m)** | **Equatorial** | 1.000 | 0.011 | < 0.001 | < 0.001 |
| **Mid-Tropical** | 0.011 | 1.000 | < 0.001 |
| **High-Tropical** | < 0.001 | < 0.001 | 1.000 |
| **> 1 km Per Motu Mean Motu Length (m)** | **Equatorial** | 1.000 | 0.011 | 1.000 | < 0.001 |
| **Mid-Tropical** | 0.011 | 1.000 | < 0.001 |
| **High-Tropical** | 1.000 | < 0.001 | 1.000 |
| **> 10% Per Object Normalized motu length/reef flat length** | **Equatorial** | 1.000 | 1.000 | 1.000 | 0.547 |
| **Mid-Tropical** | 1.000 | 1.000 | 1.000 |
| **High-Tropical** | 1.000 | 1.000 | 1.000 |
| **> 10% Per Object Normalized motu ocean reef/reef flat width** | **Equatorial** | 1.000 | 0.236 | 0.227 | < 0.001 |
| **Mid-Tropical** | 0.236 | 1.000 | < 0.001 |
| **High-Tropical** | 0.227 | < 0.001 | 1.000 |

Table S9. Kruskal-Wallis and Post-Hoc Dunn Statistical Analysis for latitude regional analysis binned per motu (n = 1,749) paired with Figure 12 comparing small and large motu.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Variable Tested** |  | **Small Motu, < 1 km** | **Large Motu, > 1 km** | **KRUSKAL WALLIS P-VALUE** |
| **All Motu Mean Ocean Reef Width** | **Small Motu, < 1 km** | 1.000 | < 0.001 | < 0.001 |
| **Large Motu, > 1 km** | < 0.001 | 1.000 |
| **Equatorial Motu Mean Ocean Reef Width** | **Small Motu, < 1 km** | 1.000 | 0.010 | 0.005 |
| **Large Motu, > 1 km** | 0.010 | 1.000 |
| **Mid Tropical Motu Mean Ocean Reef Width** | **Small Motu, < 1 km** | 1.000 | < 0.001 | < 0.001 |
| **Large Motu, > 1 km** | < 0.001 | 1.000 |
| **High Tropical Motu Mean Ocean Reef Width** | **Small Motu, < 1 km** | 1.000 | < 0.001 | < 0.001 |
| **Large Motu, > 1 km** | < 0.001 | 1.000 |
| **All Motu motu-reef-flat-dist/reef-flat width** | **Small Motu, < 1 km** | 1.000 | < 0.001 | < 0.001 |
| **Large Motu, > 1 km** | < 0.001 | 1.000 |
| **Equatorial Motu motu-reef-flat-dist/reef-flat width** | **Small Motu, < 1 km** | 1.000 | 0.019 | 0.006 |
| **Large Motu, > 1 km** | 0.019 | 1.000 |
| **Mid Tropical Motu motu-reef-flat-dist/reef-flat width** | **Small Motu, < 1 km** | 1.000 | < 0.001 | < 0.001 |
| **Large Motu, > 1 km** | < 0.001 | 1.000 |
| **High Tropical Motu motu-reef-flat-dist/reef-flat width** | **Small Motu, < 1 km** | 1.000 | < 0.001 | < 0.001 |
| **Large Motu, > 1 km** | < 0.001 | 1.000 |

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