Supplementary Material: Climate-modulated range expansion of reef-building coral communities off southeast Florida during the late Holocene

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**Sample preparation and U-Th dating**

In preparation for U-Th dating, each subfossil coral sample was sectioned laterally using a diamond tile saw, and small pieces of internal coral aragonite free of visually observable secondary alteration and dissolution were extracted along the primary growth axis. The coral pieces were soaked in an 8% sodium hypochlorite solution for ~24 hours and then sonicated in deionized water to remove any organics and detrital material. Because diagenesis is a considerable source of error in determining U-Th ages from corals, fragments from sub-samples were powdered and analyzed for evidence of secondary calcite by X-ray diffraction (XRD) using a Philips XPert Powder Diffractometer (Department of Chemistry, Rutgers). Only samples with “no detectable” calcite (less than 0.2 %, Chiu *et al*., 2005) were processed further for U-Th dating. In order to evaluate the extent of secondary aragonite precipitation (not detected by XRD), additional representative samples were imaged using a JEOL JSM 5900 LV Scanning Electron Microscope (SEM). Only minimal secondary aragonite was observed in these samples (Fig S1).

U-Th isotopic measurements were determined by Multi-collector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS) following the methods described in Mortlock *et al*. (2005) and revised in Abdul *et al*. (2016) using a ThermoScientific NEPTUNE PLUS MC-ICP-MS (Department of Earth and Planetary Sciences, Rutgers University). All but three coral sample yielded δ234U initials within the range of seawater and measured in modern corals (144 to 150‰), confirming that they maintained “closed system behavior” (Fairbanks *et al*., 2005). Based on the measured 232Th concentrations (30 to 580 ppt) no age correction was made for initial 230Th. The results are reported as ages before present (relative to 1950) with 2σ errors (Table S1).

**Age distribution analysis**

In order to construct a chronology of coral community development, the relative probability distribution of the U-Th dated subfossil corals was calculated using a non-parametric Kernel Density Estimation (KDE) approach in R (IsoplotR 3.3 package, Vermeesch, 2018). In general, the KDE works by centering a probability distribution function (kernel) with a specified range (bandwidth) over each observation and calculating their sum to produce an estimate of the original distribution. Therefore, in this study, the larger the KDE (greater clustering among ages), the higher the likelihood of a significant coral community growth episode occurring at that point in time. Because the bandwidth parameter defines how closely spaced the ages must be to constitute a significant growth episode, we selected a cutoff value based on the average distance between neighboring U-Th ages in the dataset (~80 years). With this method, distances between ages greater than the average suggest a relatively higher likelihood of coral growth occurring at that time, whereas distances less than 80 years suggest a relatively lower likelihood. We also used an adaptive bandwidth modifier (Abramson 1982) that varies the bandwidth according to the local density. This prevents over-smoothing in areas where the data are dense and under-smoothing in areas where the data are sparse (Vermeesch 2012).

**Age comparison between taxa**

Differences in U-Th ages between coral taxa (*Acropora palmata* vs. *Orbicella* spp.) were tested using a general linear model analysis of variance (ANOVA) in R (stats v3.62.2 package, R-Core). The data met the assumptions of homoscedasticity (Levene’s Test: F1,38 = 0.0277, p = 0.8686) and normality of residuals (Shapiro-Wilk Test: W = 0.97968, p = 0.6778) without needing prior transformation. Results indicate that there were no statistically significant differences in U-Th age between taxa (ANOVA, F1,38 = 2.675, p = 0.11), suggesting that both species likely coexisted throughout the duration of coral community development (Fig S2). These results also suggest that there is minimal time-averaging between branching and massive coral growth types over the centennial timescales of coral community development evaluated in this study.

**Paleodepth estimation**

In similar Holocene fossil reef studies, paleodepths are typically defined as the vertical distance between the collection depth of the coral and the estimated regional sea-level elevation corresponding to its radiometric age. Although this method produces a good general estimate of coral paleodepth in a variety of different reef settings, it assumes the corals were growing *in situ* at the same depth in which they were collected (Hubbard *et al*., 2009). Because the original growth positions for most corals dated in this study are unknown, we instead estimated the average range of paleodepths for the surrounding ridge complex across the duration of primary coral community development. This was done by subtracting the sea-level elevations from the Khan *et al*. (2017) Holocene relative sea-level reconstruction for south Florida corresponding to each coral age by the average depth of the entire study area relative to mean sea level (MSL). Average local depth of the study area was calculated using a 5-m resolution lidar-derived bathymetric digital elevation model (DEM) acquired by the U.S. Army Corp of Engineers (USACE) in 2017. The average local depth was converted from the original datum (NAVD88) to local MSL using NOAA’s online VDATUM vertical datum conversion software.

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**Figure S1.** Scanning electron microscopy (SEM) images of representative subfossil coral samples dated in this study (A) Pristine skeletal material from *A. palmata* (PMP-40) showing no secondary aragonite crystals. (B) Pristine skeletal material from *Acropora palmata* (PMP-38) showing no secondary aragonite crystals. D. (C) Pristine skeletal material from *Orbicella* spp. (PMP-37). (D) Skeletal material from *Orbicella* spp. showing minimal secondary aragonite (PMP-42). PA – pristine aragonite, SA – secondary aragonite. Images acquired by A.B.M.

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| **Table S1.** MC-ICP-MS U-Th ages obtained from dead *Acropora palmata*(Apalm)and *Orbicella*spp. (Orb) samples collected from the subfossil coral death assemblages offshore northern Broward County, Florida. All ratios are expressed as activity ratios. Ages (years before present (BP)) were calculated using the half-lives reported in Cheng *et al*., (2000). All uncertainties are reported as 2σ. |
| **Sample** | **Taxon** | **Site** | **δ234U initial** | **U (ppm)** | **232Th (ppt)** | **[234U/238U]** | **[230Th/232Th]** | **[238U/232Th]** | **[230Th/234U]** | **[230Th/238U]** | **Years BP** |
| PMP-51 | Apalm | 2 | 148.7 ± 0.7 | 3.537 ± 0.002 | 114 ± 0.5 | 1.1483 ± 0.0005 | 1033 ± 4 | 96119 ± 386 | 0.095 ± 0.0001 | 0.0109 ± 0.0001 | 975 ± 6 |
| PMP-PT6 | Orb | 4 | 150.0 ± 0.7 | 2.497 ± 0.001 | 28 ± 0.2 | 1.1493 ± 0.0005 | 4927 ± 42.6 | 274788 ± 2379 | 0.0157 ± 0.0001 | 0.0180 ± 0.0001 | 1654 ± 8 |
| PMP-02C | Apalm | 2 | 154.6 ± 0.9 | 3.316 ± 0.002 | 81 ± 1 | 1.1538 ± 0.0006 | 2553 ± 28 | 124850 ± 1380 | 0.0178 ± 0.0001 | 0.0205 ± 0.0001 | 1891 ± 8 |
| PMP-PT7 | Orb | 3 | 147.1 ± 0.7 | 2.625 ± 0.002 | 50 ± 0.1 | 1.1462 ± 0.0005 | 3617 ± 4.6 | 159806 ±229 | 0.0198 ± 0.0001 | 0.0227 ± 0.0001 | 2116 ± 9 |
| PMP-PT23 | Orb | 3 | 147.9 ± 0.9 | 2.357 ± 0.001 | 584 ± 4.2 | 1.1470 ± 0.0005 | 285.3 ± 2 | 12339 ± 89 | 0.0202 ± 0.0001 | 0.0232 ± 0.0007 | 2162 ± 6 |
| PMP-C5-P7 | Orb | 4 | 146.9 ± 0.8 | 2.629 ± 0.001 | 100 ± 0.1 | 1.1460 ± 0.0006 | 1886 ± 1.7 | 80598 ± 82 | 0.0205 ± 0.0001 | 0.0235 ± 0.0001 | 2191 ± 10 |
| PMP-PT2 | Orb | 3 | 150.0 ± 0.7 | 2.373 ± 0.001 | 178 ± 3.6 | 1.1490 ± 0.0005 | 968 ± 19.8 | 40704 ± 831 | 0.0208 ± 0.0001 | 0.0239 ± 0.0001 | 2223 ± 10 |
| PMP-05C | Apalm | 4 | 150.7 ± 0.7 | 3.809 ± 0.002 | 351 ± 0.5 | 1.1497 ± 0.0005 | 806 ± 1 | 33184 ± 47 | 0.0212 ± 0.0001 | 0.0244 ± 0.0001 | 2272 ± 8 |
| PMP-76 | Apalm | 1 | 150.5 ± 0.9 | 3.434 ± 0.003 | 166 ± 1 | 1.1495 ± 0.0006 | 1615 ± 2 | 63350 ± 79 | 0.0222 ± 0.0001 | 0.0256 + 0.0001 | 2388 ± 9 |
| PMP-64 | Apalm | 1 | 147.5 ± 0.6 | 3.393 ± 0.002 | 65 ± 0.1 | 1.1465 ± 0.0004 | 4069 ± 45 | 160111 ± 1764 | 0.0222 ± 0.0000 | 0.0255 ± 0.0000 | 2389 ± 5 |
| PMP-75 | Apalm | 1 | 148.7 ± 0.8 | 2.986 ± 0.002 | 223 ± 2 | 1.1477 ± 0.0006 | 1060 ± 8 | 40855 ± 328 | 0.0227 ± 0.0001 | 0.0260 ± 0.0001 | 2436 ± 8 |
| PMP-63 | Apalm | 1 | 149.9 ± 0.6 | 3.404 ± 0.001 | 42 ± 0.1 | 1.1488 ± 0.0004 | 6394 ± 8 | 245906 ± 331 | 0.0227 ± 0.0001 | 0.0261 + 0.0001 | 2441 ± 6 |
| PMP-PT4 | Orb | 4 | 150.0 ± 0.7 | 2.514 ± 0.001 | 85 ± 1.0 | 1.1489 ± 0.0005 | 2359 ± 29 | 90463 ± 1113 | 0.0228 ± 0.0002 | 0.0262 ± 0.0002 | 2446 ± 19 |
| PMP-61 | Apalm | 1 | 148.3 ± 0.5 | 3.348 ± 0.001 | 66 ± 1 | 1.1472 ± 0.0004 | 4047 ± 74 | 154342 ± 2840 | 0.0229 ± 0.0001 | 0.0263 ± 0.0001 | 2465 ± 6 |
| PMP-98 | Apalm | 1 | 151.6 ± 0.9 | 3.266 ± 0.002 | 520 ± 0.9 | 1.5050 ± 0.0006 | 539.6 ± 0.9 | 19184 ± 35 | 0.0245 ± 0.0001 | 0.0282 ± 0.0001 | 2642 ± 11 |
| PMP-99 | Apalm | 1 | 149.5 ± 0.9 | 3.330 ± 0.002 | 176 ± 0.3 | 1.1483 ± 0.0006 | 1662.2 ± 2.4 | 57864 ± 89 | 0.0251 ± 0.0001 | 0.0288 ± 0.0001 | 2705 ± 9 |
| PMP-03C | Orb | 4 | 147.6 ± 0.9 | 2.592 ± 0.001 | 58 ± 0.1 | 1.1464 ± 0.0007 | 4011 + 4 | 135493 ± 166 | 0.0259 ± 0.0001 | 0.0297 ± 0.0002 | 2798 ± 16 |
| PMP-42 | Apalm | 2 | 145.0 ± 0.5 | 3.581 ± 0.002 | 300 ± 0.2 | 1.1439 ± 0.0004 | 1084 ± 1 | 36539 ± 35 | 0.0260 ± 0.0000 | 0.0298 ± 0.0000 | 2811 ± 4 |
| PMP-71 | Orb | 4 | 149.5 ± 0.8 | 3.218 ± 0.002 | 276 ± 1 | 1.1482 ± 0.0005 | 1092 ± 1 | 35654 ± 40 | 0.0268 ± 0.0001 | 0.0307 ± 0.0001 | 2894 ± 8 |
| PMP-41.1 | Orb | 3 | 148.1 ± 0.4 | 3.431 ± 0.001 | 136 ± 4 | 1.1469 ± 0.0003 | 2361 ± 69 | 76916 ± 2261 | 0.0269 ± 0.0001 | 0.0308 ± 0.0001 | 2903 ± 7 |
| PMP-72 | Orb | 4 | 146.6 ± 0.5 | 2.714 ± 0.001 | 302 + 3 | 1.1453 ± 0.0004 | 865 ± 9 | 27452 ± 280 | 0.0276 ± 0.0001 | 0.0316 ± 0.0001 | 2986 ± 10 |
| PMP-04C | Apalm | 2 | 144.6 ± 0.6 | 3.876 ± 0.002 | 142 ± 0.2 | 1.1434 ± 0.0004 | 2638 ± 4 | 83063 ± 139 | 0.0279 ± 0.0001 | 0.0319 ± 0.0001 | 3017 ± 8 |
| PMP-C10 | Orb | 4 | 148.5 ± 0.7 | 2.646 ± 0.001 | 148 ± 6.5 | 1.1472 ± 0.0005 | 1758 ± 77.3 | 54657 ± 2405 | 0.0281 ± 0.0001 | 0.0323 ± 0.0001 | 3046 ± 9 |

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| **Table S1.** Continued |
| **Sample** | **Taxon** | **Site** | **δ234U initial** | **U (ppm)** | **232Th (ppt)** | **[234U/238U]** | **[230Th/232Th]** | **[238U/232Th]** | **[230Th/234U]** | **[230Th/238U]** | **Years BP** |
| PMP-01C | Apalm | 2 | 144.1 ± 0.9 | 3.903 ± 0.002 | 124 ± 12 | 1.1428 ± 0.0006 | 3114 ± 299 | 95893 ± 9206 | 0.0285 ± 0.0001 | 0.0326 + 0.0001 | 3089 ± 11 |
| PMP-39 | Orb | 3 | 149.4 ± 0.8 | 2.568 ± 0.002 | 394 ± 0.7 | 1.1480 ± 0.0005 | 655 ± 1 | 19938 ± 40 | 0.0287 ± 0.0001 | 0.0330 ± 0.0001 | 3112 ± 11 |
| PMP-97 | Apalm | 1 | 148.8 ± 1.0 | 3.159 ± 0.003 | 108 ± 0.1 | 1.1475 ± 0.0007 | 2991.4 ± 3.4 | 90538 ± 124 | 0.0289 ± 0.0001 | 0.0331 ± 0.0001 | 3130 ± 10 |
| PMP-96 | Apalm | 1 | 148.9 ± 0.7 | 3.434 ± 0.002 | 246 ± 0.3 | 1.1475 ± 0.0005 | 1416.1 ± 1.7 | 42712 ± 57 | 0.0290 ± 0.0003 | 0.0333 ± 0.0003 | 3141 ± 33 |
| PMP-38 | Orb | 3 | 147.0 ± 0.7 | 2.937 ± 0.002 | 154 ± 2.6 | 1.1457 ± 0.0005 | 1936 ± 33 | 58433 ± 982 | 0.0290 ± 0.0001 | 0.0332 ± 0.0001 | 3148 ± 12 |
| PMP-53 | Apalm | 2 | 149.4 ± 1.1 | 3.286 ± 0.002 | 103 ± 0.1 | 1.1480 ± 0.0008 | 3256 ± 3 | 97977 ± 111 | 0.0290 ± 0.0001 | 0.0333 ± 0.0001 | 3151 ± 9 |
| PMP-40 | Apalm | 2 | 148.4 ± 0.5 | 2.877 ± 0.001 | 134 ± 2 | 1.1470 ± 0.0003 | 2178 ± 27 | 65530 ± 826 | 0.0291 ± 0.0001 | 0.0334 ± 0.0001 | 3153 ± 7 |
| PMP-37 | Orb | 3 | 148.2 ± 0.6 | 2.800 ± 0.002 | 147 ± 0.1 | 1.1468 ± 0.0004 | 1958 ± 2 | 58282 ± 59 | 0.0294 ± 0.0001 | 0.0337 ± 0.0001 | 3189 ± 11 |
| PMP-C4-1A | Orb | 4 | 149.3 ± 0.9 | 2.701 ± 0.001 | 142 ± 1.1 | 1.1479 ± 0.0006 | 1960 ± 15 | 58260 ± 448 | 0.0294 ± 0.0001 | 0.0338 ± 0.0007 | 3189 ± 7 |
| PMP-C1-P1 | Orb | 4 | 147.4 ± 0.7 | 2.907 ± 0.001 | 60 ± 0.1 | 1.1460 ± 0.0005 | 5017 ± 11 | 147336 ± 329 | 0.0298 ± 0.0001 | 0.0342 ± 0.0002 | 3235 ± 14 |
| PMP-74 | Apalm | 1 | 147.4 ± 0.7 | 3.639 ± 0.001 | 555 ± 1 | 1.1459 ± 0.0005 | 710 ± 1 | 20032 ± 22 | 0.0310 + 0.0001 | 0.0356 ± 0.0001 | 3372 ± 12 |
| PMP-73 | Orb | 4 | 149.7 ± 0.7 | 2.955 ± 0.001 | 69 ± 1 | 1.1481 ± 0.0005 | 4910 ± 3 | 130816 ± 103 | 0.0328 ± 0.0000 | 0.0377 ± 0.0000 | 3572 ± 5 |
| PMP-C3-1A | Orb | 4 | 151.0 ± 0.9 | 2.585 ± 0.001 | 37 ± 0.9 | 1.1492 ± 0.0006 | 9501 ± 237.5 | 212533 ± 5314 | 0.0390 ± 0.0002 | 0.0449 ± 0.0003 | 4276 ± 24 |
| PT-100 | Apalm | 4 | 143.2 ± 0.6 | 3.769 ± 0.002 | 33 ± 0.1 | 1.1422 ± 0.0005 | 8667 ± 9.3 | 348999 ± 421 | 0.0219 ± 0.0000 | 0.0250 ± 0.0000 | 2342 ± 4 |
| PT-101 | Apalm | 3 | 151.1 ± 0.7 | 3.805 ± 0.002 | 55 ± 0.1 | 1.1501 ± 0.0005 | 5227 ± 6.0 | 211000 ± 262 | 0.0217 ± 0.0000 | 0.0249 ± 0.0000 | 2319 ± 7 |
| PT-102 | Apalm | 3 | 149.8 ± 0.7 | 3.753 ± 0.001 | 47 ± 0.0 | 1.1490 ± 0.0005 | 5185 ± 4 | 246000 ± 200 | 0.0184 ± 0.0000 | 0.0212 ± 0.0000 | 1960 ± 4 |

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**Figure S2**. Boxplot comparing U-Th ages (years before present (B.P.) between *Acropora palmata* and *Orbicella* spp. Apalm – *Acropora palmata*; Orb – *Orbicella* spp. Bold line is the median age, box represents the interquartile range, and whiskers represent 1.5x the interquartile range



**Figure S3.** Histogram of estimated paleo-depths based on Khan *et al*. (2017) Holocene sea-level curve for South Florida and local average paleo-depth determined for the study area. Dashed line represents mean paleo-depth calculated from coral age data occurring within primary range of coral community development between ~3300 and 2000 yr B.P.  (-1.9 m MSL). Binwidth = 0.2 m.