

1 Climate-forced sea level lowstands in the Indian Ocean during the last two millennia

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11 **Sea-level reconstructions over the past two millennia provide a pre-industrial context to assess**

12 **whether the magnitude and rate of modern sea-level change is unprecedented. Sea-level**

13 **records from the Indian Ocean over the past 2,000 years are sparse, while records from the**

14 **Atlantic and Pacific Oceans show variations less than 0.25 m and no significant negative**

15 **excursions. Here we present evidence of two low sea-level phases in the Maldives, Indian Ocean**

16 **based on fossil coral microatolls. Microatoll growth is constrained by low water levels and**

17 **consequently, they are robust recorders of past sea level. U-Th dating of the Maldivian corals**

18 **identified lowstands at 234-605 CE and 1481-1807 CE when sea-level fell to maximum depths of -**

19 **0.88 m and -0.89 m respectively. These lowstands are synchronous with reductions in radiative**

20 **forcing and sea surface temperature associated with the Late Antiquity Little Ice Age and Little**

21 **Ice Age. Our results provide the first high fidelity observations of lower sea levels during these**

22 **cool periods and show rates of change of up to 4.24 mm.yr⁻¹. Our data also confirms the**

23 **acceleration of relative sea-level rise over the past two centuries and suggests the current**

24 **magnitude and rate of sea-level rise is not unprecedented.**

25 Resolving the precise behaviour of relative sea level (RSL) over the past two millennia, and particularly
26 prior to the industrial era, provides a robust basis to understand natural sea-level variability and
27 evaluate whether the scale and pace of modern sea-level rise is exceptional¹⁻³. Reconstruction of late
28 Holocene RSL also provides constraints for calibrating geophysical models of Earth's rheology and
29 glacio-isostatic adjustments (GIA)^{4,5}. An enhanced understanding of the relationships between sea
30 level, climate change and oceanic processes also provides the basis for improved projections of future
31 sea level⁶⁻⁸ and the impacts on coastal systems and societies⁹⁻¹¹.

32 Despite the importance of constructing pre-industrial sea-level records, knowledge of sea-level
33 variability over the Common Era (CE, the past 2,000 years) is limited and sea-level response to known
34 climatic variations such as the Medieval Climate Anomaly (MCA), Little Ice Age (LIA) and 20th Century
35 warming is poorly constrained^{4,6}. Furthermore, large differences in RSL behaviour exist between near-
36 field, intermediate-field and far-field locations and between ocean basins¹². Studies using salt-marsh
37 proxy records, have developed high resolution records spanning the past two millennia for the North
38 American Atlantic and Gulf coasts, which show sea level continually rising throughout the mid-late
39 Holocene to its present maximum^{3,13,14}. Several notable features characterize these records. First, RSL
40 appears to have not deviated significantly from its linear trend until the onset of modern sea-level rise in
41 the late 19th century. Second, low amplitude variations $< \pm 0.25$ m have been detected, corresponding
42 to shifts in global mean temperature. Third, there is little evidence of any marked sea-level excursions
43 below present level in the late Holocene.

44 In contrast to the Atlantic, sea-level dynamics over the past 2,000 years in the Indian and Pacific
45 Oceans remain poorly resolved. Broad-scale Holocene reconstructions from these ocean basins infer
46 sea level fell smoothly from a mid-Holocene highstand^{4,15,16}, although empirical data confirming this
47 trend are scarce^{5,17,18}. Notably, many records derived for the Indo-Pacific are constructed from coral-
48 based data in tropical far-field locations. However, such observational data are not continuous and are

49 restricted to time intervals and environmental settings that favour preservation of those records⁴. For
50 example, existing coral-based sea-level reconstructions comprise a rich dataset (Supplementary Fig. 1)
51 spanning the early to mid-Holocene transgression that terminated in a highstand, at which time reefs
52 and corals grew above current sea level¹⁵⁻¹⁷. This widespread high sea-level signature is likely to have
53 occluded post-highstand coral growth from emergent reef platforms, and with it any clear-cut evidence
54 of RSL, rendering inferences of sea-level trends and variability over the last 2,000 years largely
55 speculative.

56 Coral microatolls as paleo sea-level indicators

57 We present the first field evidence of post-highstand sea-level behaviour in the Maldives, central Indian
58 Ocean (Fig. 1), that includes two periods of low sea level in the last 2,000 years. During this time both
59 empirical paleo sea-level data from the region^{15,17,18} and geophysical model results¹⁹ depict a smoothly
60 falling sea to its present position (Fig. 1D). Our new evidence, derived from high precision U-Th dating
61 of 39 *in situ* fossil coral microatolls (*Porites* spp.) that have been preserved on the Mahutigalaa reef
62 platform, Huvadhoon atoll, challenges this view (Fig. 1B, C, Supplementary Information). Such
63 microatolls are the principal geological indicator of Holocene RSL changes used in far-field tropical mid-
64 ocean settings^{4,5,20}. Details of the location, diameter, elevation and age of the fossil microatolls on
65 Mahutigalaa are summarised in Supplementary Information.

66 Timing and elevation of low and variable sea levels

67 Two spatially and temporally discrete clusters of U-Th dated fossil microatolls (39 in total ranging in
68 diameter from 1.0 to 4.95 m, with a mean of 2.66 m) identify an oscillating sea surface and two low RSL
69 excursions following the mid-late Holocene highstand (+0.5 m above mean sea level (MSL)) of 4,000 to
70 2,100 years ago¹⁷ (Fig. 2A). The first lowstand occurred between 234 to 605 CE (371 years) and is
71 defined by 11 microatolls. These microatolls cover a 0.24 m depth range and have a mean elevation of
72 -0.77 ± 0.14 m below present height of living coral (HLC), with two microatolls defining the lowest level

73 of -0.88 ± 0.14 m below HLC. These elevations equate to mean and maximum depths of -1.34 and -
74 1.45 ± 0.14 m below mean sea level (MSL). The second lowstand occurred over eight centuries later
75 from 1481 to 1807 CE (326 years), as defined by 12 microatolls, and has a mean elevation of $-0.71 \pm$
76 0.14 m below HLC. Eleven of the microatolls fit within a narrow 185 yr window (1481 to 1666 CE), are
77 found across a 0.12 m depth range and have a mean elevation of -0.69 ± 0.14 m below HLC. A further
78 microatoll (sample 10) defines a lower sea-level elevation of -0.89 ± 0.14 m below HLC at 1807 CE.
79 Seven microatolls with diameters over 4.0 m attest to prolonged sea-level stability during both
80 lowstands.

81 A temporal hiatus exists in the dataset between 784 and 1471 CE in which no coral evidence has been
82 identified on Mahutigalaa. From the earliest identified lowstand, corals indicate an increase in sea level
83 between 653 and 784 CE to an elevation -0.18 m below HLC. Corals of similar elevation dated at 1471
84 CE also record the onset of the second fall in sea level. Consequently, while there is a lack of evidence
85 in the intervening 687 year period, microatolls close to present sea level constrain the beginning and
86 end of this gap and imply sea level was near present level, if not higher, during this period. Notably, our
87 data also reveal a marked increase in sea level over the past 210 years beginning from the lowstand
88 (1807 CE) with a magnitude of sea-level rise of 0.89 m.

89 Absence of low sea level evidence on coral reefs

90 Our Maldivian results provide the first observational data that identifies two RSL excursions that fell well
91 below the present level of the sea surface. Mean and maximum depths of >0.7 to 0.89 ± 0.14 m were
92 achieved and the temporal pattern clearly indicates large oscillations in sea-level behaviour over the
93 past two millennia in the Indian Ocean. To date, such oscillations have not been detected globally and
94 coral evidence across this timeframe is limited (SI Fig. 1). We believe this general lack of reefal
95 evidence is a legacy of the mid-Holocene high sea level which had two major, but generally
96 unrecognised, effects. First, the emergence of highstand reefs as sea-level fell occluded coral growth

97 from reef surfaces. Second, any potential accommodation space that was available has been
98 overprinted by subsequent reef growth in the last two centuries. Preservation of coral records is
99 therefore, rare, except in exceptional locations such as the lagoon platform reefs in the Maldives.
100 Significantly, GIA modelling in this far-field region is unable to resolve sea-level fluctuations of the scale
101 observed¹⁹ (Fig. 1D), suggesting that the primary drivers of the two lowstands, and the timeframe of
102 oscillations, cannot be explained by glacio-isostatic, gravitational and rotational effects. Instead, global
103 climate fluctuations^{7,29} forcing variations in sea surface temperature (SST) are considered the most
104 likely mechanism driving steric sea-level variability shown in our data²⁵.

105 Low sea levels and little ice ages

106 While SST records from the central Indian Ocean are scarce, regional and global proxy data show that
107 both periods of lower sea level are coincident with intervals of substantial climate cooling (Fig. 2). The
108 Late Antique Little Ice Age (LALIA) was a long-lasting, spatially synchronized period characterised by
109 variable and colder climates that occurred from the second to the seventh centuries^{24,30-33}, (Fig. 2B).
110 This interval had 13 of the coolest decades spanning the last 2,000 years²³. Of note, volcanism has
111 been implicated in forcing the radiative cooling associated with the LALIA after which temperatures
112 increased rapidly in the seventh century³¹. Consistent with this change is the progressive increase in
113 elevation of microatolls in our coral data, leading toward the MCA, characterized by warmer
114 temperatures and a gap in the global microatoll record (SI Fig. 1, Fig. 2A). The LIA is also known to
115 have started abruptly 1275-1300 CE in response to increased volcanism and reinforced by ocean/sea-
116 ice feedbacks³⁴ and a solar minimum²⁷ and extended through to the mid-19th century³⁵. Our physical
117 records present the first evidence of falling and low sea levels in these climatic cool intervals with lower
118 SSTs (Fig. 2C).

119 Interpreting modern sea level behaviour

120 Our results have profound implications for interpreting modern and future sea-level change. The
121 magnitude of the sea-level oscillations, as revealed in our coral-based data, over the last two millennia,
122 are larger (up to 0.89 m) than earlier empirical and model reconstructions suggest. Based on maximum
123 and minimum elevation microatolls in our dataset, rates of sea-level rise and fall across the past 1800
124 years range from 4.24 to 2.80 mm.yr⁻¹ (Supplementary Table 4). Periods of sea-level fall occurred at
125 rates of -2.80 (-92 to 401 CE) and -2.75 mm.yr⁻¹ (1521-1757 CE) whilst sea-level rose at a rate of 4.24
126 mm.yr⁻¹ between 401 and 717 CE. Consequently, the magnitude and rates of sea-level change
127 currently observed in the Indian Ocean, at twice the global average³⁶, are not unprecedented over the
128 past 2,000 years. Furthermore, coastal ecosystems and communities have clearly experienced sea-
129 level oscillations that are of lower frequency but are much greater in magnitude than the El Niño
130 Southern Oscillation (ENSO) seesaw that presently characterizes sea-level variability in the Indo-
131 Pacific. Whilst ENSO-generated sea levels are expected to become more extreme with SLR in the
132 future³⁷, the possibility of large positive and negative sea-level changes of the scale demonstrated here
133 should also be considered. Additionally, we present the first coral-based record of the most recent
134 acceleration in sea level in the Indian Ocean, that began in the early 19th century (Fig. 2A). While
135 providing validity for the earlier sea-level excursions, both the magnitude and rate (4.24 mm.yr⁻¹) of this
136 recent rise is consistent with the 25 year tide gauge record from Gan (Addu atoll) located 110 km south
137 of our field site, which shows an increase in sea level of ~3.4 mm.yr⁻¹ over the past two decades.
138 Collectively, our coral evidence suggests that rates of recent sea-level change are not unprecedented
139 over the past two millennia. However, these rates of rise set a sea-level trajectory that will exceed the
140 elevation of the late Holocene highstand in the Indo-Pacific in the next century.

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230 Author contributions

231 PK conceived the project; PK, RM, SO, ER, KM undertook fieldwork; XW and LK performed U-Th
232 dating; KR undertook GIA modelling of field location; PK, RM and SO led manuscript development and
233 interpretation; all authors contributed to manuscript revision.

234 Competing interests

235 Authors declare no competing interests.

236 **Figure captions**

237 **Figure 1. Field location and Holocene sea-level history of the Maldives archipelago, Indian Ocean.** a, Location of
238 Maldives archipelago, central Indian Ocean. b, Locality of the Mahutigalaa reef platform, Huvadhoo atoll (orange box),
239 southern Maldives and location of emergent mid-late Holocene corals in central Maldives¹⁷ (orange triangle). Base data
240 British Admiralty Chart 709. c, Oblique aerial photograph of the Mahutigalaa reef platform (source: P. Kench 2016). d,
241 Summary Holocene sea-level curve for the Maldives based on published coral data^{17,18} and output from the glacial isostatic
242 adjustment (GIA) model ICE-6G_C (VM5a) for Mahutigalaa^{21,22}, see Methods for details. msl is mean sea level. Years (CE)
243 is Common Era and Cal. Years BP denotes calibrated years before 1950. No observational data indicates no physical coral
244 evidence to support sea-level reconstructions, dated from the last 1800 years, has been reported from the Maldives.

245 **Figure 2. Reconstructed sea level in the central Indian Ocean and global paleoclimate variability over the past 2500**
246 **years.** a, elevation and age of fossil microatolls from Mahutigalaa reef platform, Maldives. Red boxes are two fossil
247 microatolls from Funadhoo reef (central Maldives, Fig. 1A) that mark the end of the mid-late Holocene highstand and dated
248 using AMS¹⁷; orange boxes are microatolls dated using U-Th method in this study (Supplementary Table 1), vertical error
249 bars ± 0.14 m. Age error bars are smaller than the size of symbols and width of boxes reflect microatoll diameter. Dashed
250 boxes define corals included in lowstand calculations. Cal. Years BP is calibrated years before 1950. b, Reconstructed
251 northern hemisphere (European) June, July, August temperature anomalies (red line and left x-axis) relative to the 1901-
252 2000 period (grey dashed line), error is ± 1 root mean square error (RMSE, red dashed lines)²³; and northern hemisphere
253 decadal temperature variations (blue line, right x-axis) with 2δ error (blue shading)²⁴. c, 2,000-year sea surface temperature
254 reconstruction in Makassar Strait, Indonesia²⁵ (blue line); SST reconstruction²⁶, for the West Pacific Warm Pool (red line)
255 and southern Makassar Strait (orange line). d, Total solar irradiance²⁷ (blue line), occurrence of major volcanic events
256 through the Holocene (green bars) and volcanic events making major contributions to stratospheric sulfate levels based on
257 $\Delta^{17}\text{O}$ analyses (brown squares), error bars are 1 s.d.²⁸. Vertical grey shading denotes time periods of lower sea levels in the
258 Mahutigalaa coral record and climatic cool periods. LIA = Little Ice Age, MCA = Medieval Climate Anomaly, LALIA = Late
259 Antiquity Little Ice Age.

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264 **Methods**

265 **Glacio-isostatic adjustment modelling**

266 Glacio-isostatic adjustment (GIA) modelling for the field location was undertaken using the ICE-6G_C
267 (VM5a) model²¹ by one of the authors (KR) and presented in Figure 1D. The model is global in nature,
268 takes into account a full suite of geophysical impacts related to GIA (self-gravitation, migrating
269 shorelines, rotational feedback, etc.), and provides fully consistent sea-level histories globally²¹. The
270 model is based upon iterative refinements against a global suite of constraints (e.g. relative sea level,
271 rotational observables, space-geodesy), and successive incremental iterations of the model have
272 shown the general convergence of the methodology^{21,22}.

273 **Field sampling of corals**

274 Field surveys and sampling were undertaken during three field campaigns in 2016-2018. Detailed
275 description of the field site and a discussion of the environmental context of the fossil microatolls and
276 causes of variability in elevation are presented in the Supplementary Information. A total of 49 fossil
277 microatolls were identified on the reef platform ranging in diameter from 0.9 to 4.95 m (Supplementary
278 Table 1, Supplementary Figs 2 and 3). All fossil microatolls were found in currently free draining
279 locations. The diameter of microatolls reflects the period of growth of each colony at its limiting water
280 level. Consequently, larger diameter microatolls reflect a longer period of sea-level stability at which
281 that colony grew. For example, the larger-sized microatolls (e.g. ~5.0 m) reflect growth over a period of
282 ~170 years assuming average skeletal extension of 1.5 cm/yr. For each specimen the location was
283 documented using a Trimble Global Positioning System (GPS) survey with a horizontal accuracy of
284 ± 1.5 m and the diameter was recorded. Plug cores (3 cm x 6 cm) were extracted from the microatoll
285 surface using a Nemo V2 handheld underwater drill. Cores were extracted from the centre and outer
286 edge of each specimen to record the initial timing that the microatolls achieved their vertical growth limit

287 (centre) and the timing of colony death (outer edge). Cores were bathed in hydrogen peroxide for 24
288 hours to neutralise organic material, rinsed, dried and stored for dating.

289 The elevation of fossil microatolls was determined using a combination of Real Time Kinematic (RTK)
290 GPS and laser level surveys. Three benchmarks were inserted into the vegetated cay and static
291 surveys undertaken using RTK GPS over a 12-hour period to determine the elevation of each
292 benchmark with respect to sea level. The vertical elevation error of these surveys was ± 0.02 m. As
293 microatolls were found in water depths ranging up to 2.0 m below high tide, RTK GPS survey was not
294 possible, thus laser level surveys (vertical error of ± 0.03 m) were used to connect the elevation of
295 microatoll upper surfaces to island benchmarks. The elevation of each colony was determined at its
296 central core and outer edge (mean of 5 measurements) and linked directly to the nearest land-based
297 benchmark. Of note, surveys were repeated on three occasions (each field season) to resolve survey
298 error and relative differences between fossil microatoll colonies.

299 A biological elevation reference (height of living coral, HLC) was established for the field site based on
300 surveys of the elevation of the living upper surface of 30 live *Porites* spp. microatolls, within 50 m of the
301 fossil coral locations. At each coral a minimum of five elevation points were recorded around each
302 specimen to account for within colony variability. The elevation range of the upper surface of living
303 *Porites* colonies was ± 0.095 m. The surveys were undertaken in each field season to examine
304 consistency in elevation data. This sampling strategy provides a reproducible method and ensures a
305 direct comparative basis between the growth elevation of fossil and modern microatolls. The HLC was
306 calculated as the average elevation of living *Porites* spp. microatolls and records the contemporary
307 upper growth limit for microatolls, which inversely represents the constraining water level for coral
308 growth. The HLC for Mahutigalaa was calculated as 0.567 ± 0.095 m below mean sea level, which is
309 close to Mean Low Water Spring (MLWS) tide level. The elevation of fossil microatolls is presented as
310 both a difference from present MSL and HLC. The combined survey error in evaluating change in
311 elevation between fossil and living microatolls is calculated as ± 0.14 m.

312 Uranium-Thorium dating method

313 A total of 49 ^{230}Th ages were determined for 37 corals (including 12 replicate analyses, Supplementary
314 Data 1). Samples were gently crushed into 1 to 3-mm³ segments. Clean and pristine pieces were
315 selected under microscope, and subsequently ultrasonically cleaned (three times) in superclean
316 water. For each sample, 30 to 60 mg was used for U-Th chemistry^{40,41}. Replicates were prepared for
317 six subsamples (1,12,13,14,16, and 18). All samples were dissolved in ultrapure nitric acids and a
318 ^{229}Th - ^{233}U - ^{236}U mixed spike was then added to the solutions. HClO_4 was also added to remove organic
319 compounds. Each sample solution was refluxed at 175°C for 2 hours and dried. Samples were re-
320 dissolved by adding 2N ultrapure HCl solution. Co-precipitation was achieved by adding FeCl_3 and
321 concentrated NH_4OH . Co-precipitates were re-dissolved and put through an anion-exchange resin in
322 columns to separate and purify uranium and thorium. U and Th fractions were then dissolved in
323 1% HNO_3 (+0.1% HF) for instrumental analysis. U and Th isotopic compositions were determined on a
324 multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS, a Neptune Plus from
325 Thermo Fisher Scientific) at the Earth Observatory of Singapore and Asian School of the Environment
326 (ASE), Nanyang Technological University, Singapore. The measurements were undertaken using a
327 recently improved SEM peak-jumping technique^{42,43}. Uncertainties in the U and Th isotopic data and
328 ^{230}Th dates are quoted at the 2σ level in this paper.

329 Estimating the growth age of microatolls

330 U-Th dating determined the age of the centre of each microatoll as this site represents the time at
331 which the coral was first constrained by water level. The diameter and flat surface of each microatoll
332 represents a period of time that sea level was stable and continued to constrain vertical growth. The
333 outer edge of each colony therefore, represents the terminal age of an individual coral at a specific
334 water level. This terminal age may also correspond to the end of a particular sea level stand.

335 An estimate of the age of the outer edge of each microatoll was calculated from the distance between
336 the central sample (of known ^{230}Th age) and outer edge of the colony, divided by an average extension
337 rate of 1.5 cm.yr^{-1} (range $0.5\text{-}2.5 \text{ cm.yr}^{-1}$), as previously reported for massive corals in the mid-
338 Holocene^{44,45} and recently reported from contemporary growth estimates in the Maldives⁴⁶.

339 To validate these estimates accelerator mass spectrometry (AMS) radiocarbon dating of the outer edge
340 of six microatolls (Supplementary Table 2) was compared with the ^{230}Th ages of the centre of the same
341 coral (Supplementary Table 1). The difference in age across the distance between samples on each
342 microatoll surface provides an estimate of average extension rates (Supplementary Table 3). Of note
343 the estimated extension rates ranged from 1.23 to 1.99 cm.yr^{-1} , with an average of 1.47 cm.yr^{-1} ,
344 consistent with previous historic estimates and contemporary measurements from the Maldives⁴⁶ and
345 supports the use of an average value of 1.5 cm.yr^{-1} in this study.

346 Determination of sea-level lowstands

347 Two measures were adopted to define the elevation of lower sea level from the coral evidence. First,
348 the mean elevation of all microatolls defining a specific sea-level lowstand was calculated to account for
349 variations in microatoll elevation. Of note, corals considered to be impacted by localised ponding were
350 excluded from calculations of sea-level position, consistent with previous studies²⁹. Second, estimates
351 of the maximum sea-level fall in each period were established based on the deepest microatoll
352 documented in each lowstand period.

353 Determination of rates of sea-level change

354 Determination of rates of sea-level change from the coral records was based on age and depth
355 constraints of corals and the growth age of corals, as reflected in the diameter of each colony
356 (Supplementary Table 4). Both the highest and deepest microatolls were identified as markers of the
357 maximum variations in sea level throughout the record. The onset of changes in sea level were
358 determined based on the age of the outer edge of the highest or deepest microatoll. The stabilization of

359 sea level was denoted by the central ^{230}Th age of the deepest (sea-level fall) or highest (sea-level rise)
360 corals. The selection of the central age is consistent with the time that coral colonies were constrained
361 by sea level.

362 Data availability statement

363 The authors declare that the data supporting the findings of this study are available within the paper
364 and its supplementary information files.

365 Methods References

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