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

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Sea-level reconstructions over the past two millennia provide a pre-industrial context to assess whether the magnitude and rate of modern sea-level change is unprecedented. Sea-level records from the Indian Ocean over the past 2,000 years are sparse, while records from the Atlantic and Pacific Oceans show variations less than 0.25 m and no significant negative excursions. Here we present evidence of two low sea-level phases in the Maldives, Indian Ocean based on fossil coral microatolls. Microatoll growth is constrained by low water levels and consequently, they are robust recorders of past sea level. U-Th dating of the Maldivian corals identified lowstands at 234-605 CE and 1481-1807 CE when sea-level fell to maximum depths of -0.88 m and -0.89 m respectively. These lowstands are synchronous with reductions in radiative forcing and sea surface temperature associated with the Late Antiquity Little Ice Age and Little Ice Age. Our results provide the first high fidelity observations of lower sea levels during these cool periods and show rates of change of up to 4.24 $mm.yr^{-1}$. Our data also confirms the acceleration of relative sea-level rise over the past two centuries and suggests the current magnitude and rate of sea-level rise is not unprecedented.

Resolving the precise behaviour of relative sea level (RSL) over the past two millennia, and particularly prior to the industrial era, provides a robust basis to understand natural sea-level variability and evaluate whether the scale and pace of modern sea-level rise is exceptional[1-3]. Reconstruction of late Holocene RSL also provides constraints for calibrating geophysical models of Earth's rheology and glacio-isostatic adjustments (GIA)[4,5]. An enhanced understanding of the relationships between sea level, climate change and oceanic processes also provides the basis for improved projections of future sea level[6-8] and the impacts on coastal systems and societies[9-11].

Despite the importance of constructing pre-industrial sea-level records, knowledge of sea-level variability over the Common Era (CE, the past 2,000 years) is limited and sea-level response to known climatic variations such as the Medieval Climate Anomaly (MCA), Little Ice Age (LIA) and 20th Century warming is poorly constrained[4,6]. Furthermore, large differences in RSL behaviour exist between near-field, intermediate-field and far-field locations and between ocean basins[12]. Studies using salt-marsh proxy records, have developed high resolution records spanning the past two millennia for the North American Atlantic and Gulf coasts, which show sea level continually rising throughout the mid-late Holocene to its present maximum[3,13,14]. Several notable features characterize these records. First, RSL appears to have not deviated significantly from its linear trend until the onset of modern sea-level rise in the late 19th century. Second, low amplitude variations $< \pm 0.25$ m have been detected, corresponding to shifts in global mean temperature. Third, there is little evidence of any marked sea-level excursions below present level in the late Holocene.

In contrast to the Atlantic, sea-level dynamics over the past 2,000 years in the Indian and Pacific Oceans remain poorly resolved. Broad-scale Holocene reconstructions from these ocean basins infer sea level fell smoothly from a mid-Holocene highstand[4,15,16], although empirical data confirming this trend are scarce[5,17,18]. Notably, many records derived for the Indo-Pacific are constructed from coral-based data in tropical far-field locations. However, such observational data are not continuous and are restricted to time intervals and environmental settings that favour preservation of those records[4]. For example, existing coral-based sea-level reconstructions comprise a rich dataset (Supplementary Fig. 1) spanning the early to mid-Holocene transgression that terminated in a highstand, at which time reefs and corals grew above current sea level[15-17]. This widespread high sea-level signature is likely to have occluded post-highstand coral growth from emergent reef platforms, and with it any clear-cut evidence of RSL, rendering inferences of sea-level trends and variability over the last 2,000 years largely speculative.

Coral microatolls as paleo sea-level indicators

We present the first field evidence of post-highstand sea-level behaviour in the Maldives, central Indian Ocean (Fig. 1), that includes two periods of low sea level in the last 2,000 years. During this time both empirical paleo sea-level data from the region[15,17,18] and geophysical model results[19] depict a smoothly falling sea to its present position (Fig. 1D). Our new evidence, derived from high precision U-Th dating of 39 *in situ* fossil coral microatolls (*Porites* spp.) that have been preserved on the Mahutigalaa reef platform, Huvadhoo atoll, challenges this view (Fig. 1B, C, Supplementary Information). Such microatolls are the principal geological indicator of Holocene RSL changes used in far-field tropical mid-ocean settings[4,5,20]. Details of the location, diameter, elevation and age of the fossil microatolls on Mahutigalaa are summarised in Supplementary Information.

Timing and elevation of low and variable sea levels

Two spatially and temporally discrete clusters of U-Th dated fossil microatolls (39 in total ranging in diameter from 1.0 to 4.95 m, with a mean of 2.66 m) identify an oscillating sea surface and two low RSL excursions following the mid-late Holocene highstand (+0.5 m above mean sea level (MSL)) of 4,000 to 2,100 years ago[17] (Fig. 2A). The first lowstand occurred between 234 to 605 CE (371 years) and is defined by 11 microatolls. These microatolls cover a 0.24 m depth range and have a mean elevation of -0.77 ± 0.14 m below present height of living coral (HLC), with two microatolls defining the lowest level of -0.88 ± 0.14 m below HLC. These elevations equate to mean and maximum depths of -1.34 and -1.45 ± 0.14 m below mean sea level (MSL). The second lowstand occurred over eight centuries later from 1481 to 1807 CE (326 years), as defined by 12 microatolls, and has a mean elevation of -0.71 ± 0.14 m below HLC. Eleven of the microatolls fit within a narrow 185 yr window (1481 to 1666 CE), are found across a 0.12 m depth range and have a mean elevation of -0.69 ± 0.14 m below HLC. A further microatoll (sample 10) defines a lower sea-level elevation of -0.89 ± 0.14 m below HLC at 1807 CE. Seven microatolls with diameters over 4.0 m attest to prolonged sea-level stability during both lowstands.

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

Absence of low sea level evidence on coral reefs

Our Maldivian results provide the first observational data that identifies two RSL excursions that fell well below the present level of the sea surface. Mean and maximum depths of >0.7 to 0.89 ± 0.14 m were achieved and the temporal pattern clearly indicates large oscillations in sea-level behaviour over the past two millennia in the Indian Ocean. To date, such oscillations have not been detected globally and coral evidence across this timeframe is limited (SI Fig. 1). We believe this general lack of reefal evidence is a legacy of the mid-Holocene high sea level which had two major, but generally unrecognised, effects. First, the emergence of highstand reefs as sea-level fell occluded coral growth from reef surfaces. Second, any potential accommodation space that was available has been overprinted by subsequent reef growth in the last two centuries. Preservation of coral records is therefore, rare, except in exceptional locations such as the lagoon platform reefs in the Maldives. Significantly, GIA modelling in this far-field region is unable to resolve sea-level fluctuations of the scale observed[19] (Fig. 1D), suggesting that the primary drivers of the two lowstands, and the timeframe of oscillations, cannot be explained by glacio-isostatic, gravitational and rotational effects. Instead, global climate fluctuations[7,29] forcing variations in sea surface temperature (SST) are considered the most likely mechanism driving steric sea-level variability shown in our data[25].

Low sea levels and little ice ages

While SST records from the central Indian Ocean are scarce, regional and global proxy data show that both periods of lower sea level are coincident with intervals of substantial climate cooling (Fig. 2). The Late Antique Little Ice Age (LALIA) was a long-lasting, spatially synchronized period characterised by variable and colder climates that occurred from the second to the seventh centuries[24,30-33,] (Fig. 2B). This interval had 13 of the coolest decades spanning the last 2,000 years[23]. Of note, volcanism has been implicated in forcing the radiative cooling associated with the LALIA after which temperatures increased rapidly in the seventh century[31]. Consistent with this change is the progressive increase in elevation of microatolls in our coral data, leading toward the MCA, characterized by warmer temperatures and a gap in the global microatoll record (SI Fig. 1, Fig. 2A). The LIA is also known to have started abruptly 1275-1300 CE in response to increased volcanism and reinforced by ocean/sea-ice feedbacks[34] and a solar minimum[27] and extended through to the mid-19th century[35]. Our physical records present the first evidence of falling and low sea levels in these climatic cool intervals with lower SSTs (Fig. 2C).

Interpreting modern sea level behaviour

Our results have profound implications for interpreting modern and future sea-level change. The magnitude of the sea-level oscillations, as revealed in our coral-based data, over the last two millennia, are larger (up to 0.89 m) than earlier empirical and model reconstructions suggest. Based on maximum and minimum elevation microatolls in our dataset, rates of sea-level rise and fall across the past 1800 years range from 4.24 to 2.80 $mm.yr^{-1}$ (Supplementary Table 4). Periods of sea-level fall occurred at 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 $mm.yr^{-1}$ between 401 and 717 CE. Consequently, the magnitude and rates of sea-level change currently observed in the Indian Ocean, at twice the global average[36], are not unprecedented over the past 2,000 years. Furthermore, coastal ecosystems and communities have clearly experienced sea-level oscillations that are of lower frequency but are much greater in magnitude than the El Niño Southern Oscillation (ENSO) seesaw that presently characterizes sea-level variability in the Indo-Pacific. Whilst ENSO-generated sea levels are expected to become more extreme with SLR in the future[37], the possibility of large positive and negative sea-level changes of the scale demonstrated here should also be considered. Additionally, we present the first coral-based record of the most recent acceleration in sea level in the Indian Ocean, that began in the early 19th century (Fig. 2A). While providing validity for the earlier sea-level excursions, both the magnitude and rate (4.24 $mm.yr^{-1}$) of this recent rise is consistent with the 25 year tide gauge record from Gan (Addu atoll) located 110 km south of our field site, which shows an increase in sea level of ~3.4 $mm.yr^{-1}$ over the past two decades. Collectively, our coral evidence suggests that rates of recent sea-level change are not unprecedented over the past two millennia. However, these rates of rise set a sea-level trajectory that will exceed the elevation of the late Holocene highstand in the Indo-Pacific in the next century.

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Author contributions

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

Competing interests

Authors declare no competing interests.

Figure captions

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

Figure 2. Reconstructed sea level in the central Indian Ocean and global paleoclimate variability over the past 2500 years. **a**, elevation and age of fossil microatolls from Mahutigalaa reef platform, Maldives. Red boxes are two fossil microatolls from Funadhoo reef (central Maldives, Fig. 1A) that mark the end of the mid-late Holocene highstand and dated using AMS[17]; orange boxes are microatolls dated using U-Th method in this study (Supplementary Table 1), vertical error bars ±0.14 m. Age error bars are smaller than the size of symbols and width of boxes reflect microatoll diameter. Dashed boxes define corals included in lowstand calculations. Cal. Years BP is calibrated years before 1950. **b**, Reconstructed northern hemisphere (European) June, July, August temperature anomalies (red line and left x-axis) relative to the 1901-2000 period (grey dashed line), error is ±1 root mean square error (RMSE, red dashed lines)[23]; and northern hemisphere decadal temperature variations (blue line, right x-axis) with 2δ error (blue shading)[24]. **c**, 2,000-year sea surface temperature reconstruction in Makassar Strait, Indonesia[25] (blue line); SST reconstruction[26], for the West Pacific Warm Pool (red line) and southern Makassar Strait (orange line). **d**, Total solar irradiance[27] (blue line), occurrence of major volcanic events through the Holocene (green bars) and volcanic events making major contributions to stratospheric sulfate levels based on $\Delta^{17}O$ analyses (brown squares), error bars are 1 s.d.[28]. Vertical grey shading denotes time periods of lower sea levels in the Mahutigalaa coral record and climatic cool periods. LIA = Little Ice Age, MCA = Medieval Climate Anomaly, LALIA = Late Antiquity Little Ice Age.

Methods

Glacio-isostatic adjustment modelling

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

Field sampling of corals

Field surveys and sampling were undertaken during three field campaigns in 2016-2018. Detailed description of the field site and a discussion of the environmental context of the fossil microatolls and causes of variability in elevation are presented in the Supplementary Information. A total of 49 fossil microatolls were identified on the reef platform ranging in diameter from 0.9 to 4.95 m (Supplementary Table 1, Supplementary Figs 2 and 3). All fossil microatolls were found in currently free draining locations. The diameter of microatolls reflects the period of growth of each colony at its limiting water level. Consequently, larger diameter microatolls reflect a longer period of sea-level stability at which that colony grew. For example, the larger-sized microatolls (e.g. ~5.0 m) reflect growth over a period of ~170 years assuming average skeletal extension of 1.5 cm/yr. For each specimen the location was documented using a Trimble Global Positioning System (GPS) survey with a horizontal accuracy of ±1.5 m and the diameter was recorded. Plug cores (3 cm x 6 cm) were extracted from the microatoll surface using a Nemo V2 handheld underwater drill. Cores were extracted from the centre and outer edge of each specimen to record the initial timing that the microatolls achieved their vertical growth limit (centre) and the timing of colony death (outer edge). Cores were bathed in hydrogen peroxide for 24 hours to neutralise organic material, rinsed, dried and stored for dating.

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

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

Uranium-Thorium dating method

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

Estimating the growth age of microatolls

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

An estimate of the age of the outer edge of each microatoll was calculated from the distance between the central sample (of known ^{230}Th age) and outer edge of the colony, divided by an average extension rate of 1.5 cm.yr^{-1} (range 0.5-2.5 cm.yr^{-1}), as previously reported for massive corals in the mid-Holocene[44,45] and recently reported from contemporary growth estimates in the Maldives[46].

To validate these estimates accelerator mass spectrometry (AMS) radiocarbon dating of the outer edge of six microatolls (Supplementary Table 2) was compared with the ^{230}Th ages of the centre of the same coral (Supplementary Table 1). The difference in age across the distance between samples on each microatoll surface provides an estimate of average extension rates (Supplementary Table 3). Of note the estimated extension rates ranged from 1.23 to 1.99 cm.yr^{-1}, with an average of 1.47 cm.yr^{-1}, consistent with previous historic estimates and contemporary measurements from the Maldives[46] and supports the use of an average value of 1.5 cm.yr^{-1} in this study.

Determination of sea-level lowstands

Two measures were adopted to define the elevation of lower sea level from the coral evidence. First, the mean elevation of all microatolls defining a specific sea-level lowstand was calculated to account for variations in microatoll elevation. Of note, corals considered to be impacted by localised ponding were excluded from calculations of sea-level position, consistent with previous studies[29]. Second, estimates of the maximum sea-level fall in each period were established based on the deepest microatoll documented in each lowstand period.

Determination of rates of sea-level change

Determination of rates of sea-level change from the coral records was based on age and depth constraints of corals and the growth age of corals, as reflected in the diameter of each colony (Supplementary Table 4). Both the highest and deepest microatolls were identified as markers of the maximum variations in sea level throughout the record. The onset of changes in sea level were determined based on the age of the outer edge of the highest or deepest microatoll. The stabilization of sea level was denoted by the central ^{230}Th age of the deepest (sea-level fall) or highest (sea-level rise) corals. The selection of the central age is consistent with the time that coral colonies were constrained by sea level.

Data availability statement

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

Methods References

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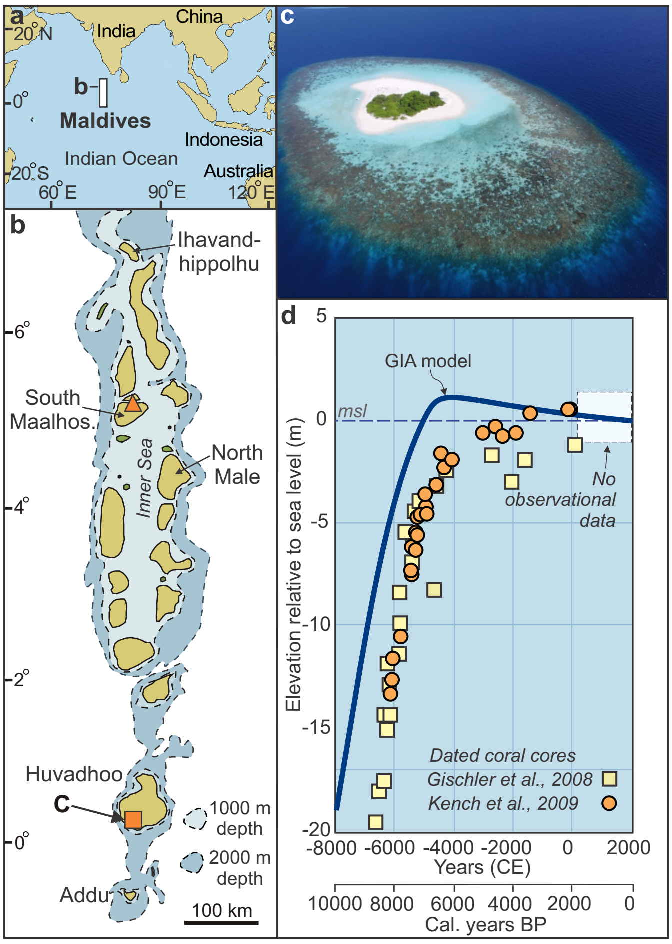
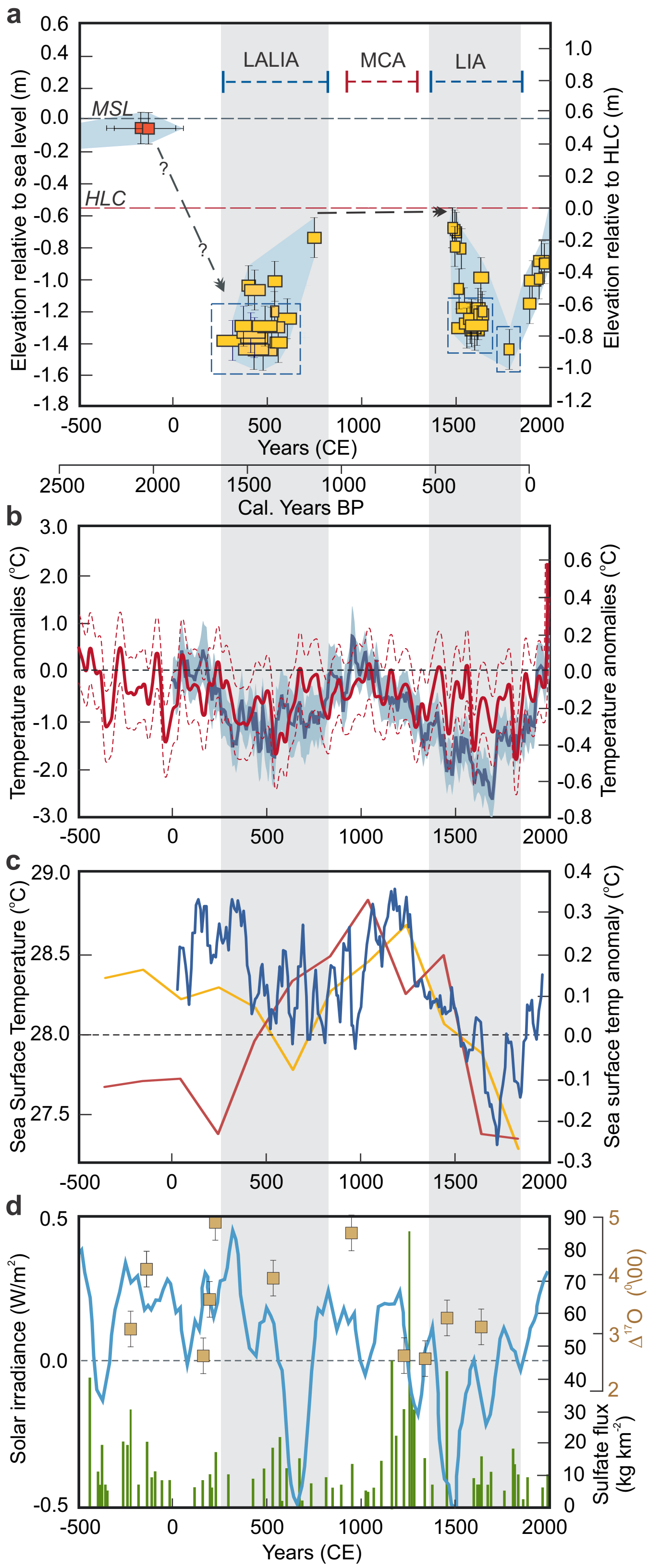


a
20°N
India
China
b
0°
Maldives
Indonesia
20°S
Indian Ocean
Australia
60°E
90°E
120°E
c
b
Ihavand-
hippolhu
6°
South
Maalhos.
North
Male
Inner Sea
4°
2°
Huvadhoo
C
0°
1000 m
depth
2000 m
depth
Addu
100 km
d
GIA model
msl
No
observational
data
Elevation relative to sea level (m)
Dated coral cores
Gischler et al., 2008
Kench et al., 2009
5
0
-5
-10
-15
-20
-8000 -6000 -4000 -2000 0 2000
Years (CE)
10000 8000 6000 4000 2000 0
Cal. years BP


a
b
c
d
LALIA
MCA
LIA
MSL
HLC
Elevation relative to sea level (m)
Elevation relative to HLC (m)
Years (CE)
Cal. Years BP
Temperature anomalies (°C)
Sea Surface Temperature (°C)
Sea surface temp anomaly (°C)
Solar irradiance (W/m²)
Sulfate flux (kg km⁻²)
Δ¹⁷O (‰)
Years (CE)