

1 **Coversheet for “Climate forcing insufficient to drive ap-**
2 **parent Common-Era sea-level lowstands in Maldives”**

3 Christopher G. Piecuch^{1,†}, Andrew C. Kemp^{2,‡}, Geoffrey Gebbie^{1,*}, & Aron J. Meltzner^{3,4,⊗}

4 ¹*Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole,*
5 *Massachusetts, USA*

6 ²*Department of Earth and Ocean Sciences, Tufts University, Medford, Massachusetts, USA*

7 ³*Earth Observatory of Singapore, Nanyang Technological University, Singapore*

8 ⁴*Asian School of the Environment, Nanyang Technological University, Singapore*

9 This paper submitted to Earth and Space Science Open Archive (ESSOAr) has undergone
10 one round of peer review and is now under revision at Nature Geoscience as a “Matters Arising.”

11 † cpiecuch@whoi.edu

12 ‡ andrew.kemp@tufts.edu

13 * jgebbie@whoi.edu

14 ⊗ meltzner@ntu.edu.sg

Climate forcing insufficient to drive apparent Common-Era sea-level lowstands in Maldives

Christopher G. Piecuch¹, Andrew C. Kemp², Geoffrey Gebbie¹, & Aron J. Meltzner^{3,4}

¹*Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA*

²*Department of Earth and Ocean Sciences, Tufts University, Medford, Massachusetts, USA*

³*Earth Observatory of Singapore, Nanyang Technological University, Singapore*

⁴*Asian School of the Environment, Nanyang Technological University, Singapore*

Reconstructions of Common-Era sea level are informative of relationships between sea level and natural climate variation, and the uniqueness of modern sea-level rise¹. Kench et al.² recently reconstructed Common-Era sea level in the Maldives, Indian Ocean, using coral microatolls. They reported periods of 150–500 yr when sea level fell and rose at average rates of 2.7–4.3 mm yr⁻¹. These periods coincided with intervals of cooling and warming inferred from proxy reconstructions of sea-surface temperature (SST) and radiative forcing (ref. 2, Fig. 2). Kench et al.² reasoned that these 0.6–1.4-m centennial-scale sea-level fluctuations were driven by climate, specifically thermal contraction and expansion of seawater. In contrast to previous studies^{3,4}, Kench et al.² argued that modern rates and magnitudes of sea-level rise caused by climate change have precedent during the Common Era. We use principles of sea-level physics to argue that pre-industrial radiative forcing and SST changes were insufficient to cause thermosteric sea-level (TSL) trends as large as reported for the Maldives².

21 Radiative forcing (e.g., related to solar activity⁵ and volcanic eruptions⁶) varies over a broad
22 range of time scales, and influences global climate and sea level^{7,8}. For example, models show that
23 major volcanic eruptions during the twentieth century drove rapid interannual falls in global-mean
24 sea level (order mm yr^{-1}) that were followed by gradual decadal rises (order tenths of mm yr^{-1}) as
25 the climate system recovered⁷. To determine whether variability in radiative forcing on centennial
26 and longer time scales in the Common Era was sufficient to drive TSL trends as large and sustained
27 as those inferred for the Maldives², we express trends in TSL in terms of their equivalent net surface
28 heat flux (see Supplementary Information). Using a thermal expansion coefficient characteristic of
29 tropical surface ocean waters ($3.1\text{--}3.4 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$), we estimate that a net flux of $1.0\text{--}1.8 \text{ W m}^{-2}$
30 is required for a TSL trend of $2.7\text{--}4.3 \text{ mm yr}^{-1}$. The required flux is stronger than centennial-scale
31 variations in reconstructions of radiative forcing^{5,6}, which can be uncertain, but exhibit magnitudes
32 < 0.4 and $< 0.2 \text{ W m}^{-2}$ over time scales of 150 and 500 yr, respectively (95% confidence; Fig. 1a;
33 Supplementary Information). In other words, radiative forcing likely accounts for $< 31\%$ ($< 18\%$)
34 of the forcing required to produce 150-yr (500-yr) TSL trends of $2.7\text{--}4.3 \text{ mm yr}^{-1}$ (Fig. 1c, purple).
35 This required net heat flux is also larger than the rate of contemporary global upper-ocean warming
36 since 2005 CE ($0.5\text{--}0.7 \text{ W m}^{-2}$) estimated from profiling-float observations⁹.

37 We also estimate what SST trend is required to generate a given trend in TSL (Supplementary
38 Information). We assume that magnitudes of ocean temperature changes decay exponentially from
39 the surface to the bottom over an *e*-folding depth scale of 750–1250 m. This translates to 45–61%
40 (83–94%) of ocean heat storage occurring in the upper 700 m (2000 m), similar to estimates from
41 model-data syntheses^{10,11} of changes in global ocean heat content over the past 140–270 yr. Using

42 a reasonable global-ocean, volume-averaged thermal expansion coefficient ($1.6\text{--}1.9 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$),
43 we find that TSL trends of $2.7\text{--}4.3 \text{ mm yr}^{-1}$ require attendant SST trends of $1.2\text{--}3.6 \text{ }^\circ\text{C century}^{-1}$
44 (Fig. 1b). This estimate is supported by long integrations of an empirical ocean circulation model¹²,
45 which suggest that TSL trends of $2.7\text{--}4.3 \text{ mm yr}^{-1}$ sustained for 150 and 500 yr require SST trends
46 of $1.8\text{--}2.9$ and $0.9\text{--}1.4 \text{ }^\circ\text{C century}^{-1}$, respectively (Fig. 1b; Supplementary Information). These
47 model results are consistent with the basic expectation that, on longer time scales under sustained
48 climate forcing, relatively more heat penetrates the deep ocean, requiring a comparatively smaller
49 SST change to produce a given TSL trend.

50 The required SST trends are larger than observed in ten reconstructions of Common-Era
51 SST¹³ in the Indian Ocean and Indonesian Throughflow, which show trends of < 0.8 and $< 0.2 \text{ }^\circ\text{C}$
52 century^{-1} on time scales of 150 and 500 yr, respectively (95% confidence; Fig. 1b; Supplementary
53 Information). Although they are not from the Maldives, these SST reconstructions are informative
54 of the range of reconstructed centennial SST trends over the tropical Indian Ocean during the
55 Common Era. We find that SST reconstructions likely account for $< 37\%$ and $< 7\%$ of the
56 temperature trends needed to explain TSL trends of $2.7\text{--}4.3 \text{ mm yr}^{-1}$ on time scales of 150 and 500
57 yr, respectively, assuming exponential vertical structure (Fig. 1c, blue). Using the empirical ocean
58 circulation model, we estimate corresponding percentages of $< 33\%$ and $< 13\%$ (Fig. 1c, orange).
59 Even making the extreme assumption that ocean temperature trends are vertically uniform, which
60 is unrealistic given the long adjustment time scales in the deep ocean¹², we find that SST trends
61 required for trends in TSL of $2.7\text{--}4.3 \text{ mm yr}^{-1}$ (Fig. 1b) are generally larger than are inferred from
62 SST reconstructions, especially for periods $> 300 \text{ yr}$ (Fig. 1c, green).

63 Kench et al.² reconstructed a sea-level trend of 4.2 mm yr⁻¹ in the Maldives for the modern
64 industrial interval between 1807 and 2018 CE. Comparable trends of 3.2–4.7 mm yr⁻¹ are seen in
65 two tide-gauge sea-level records¹⁴ in the Maldives for the past 25–30 yr (Supplementary Table S1).
66 However, smaller sea-level trends of 0.6–1.5 mm yr⁻¹ are seen for the past 80–140 yr in four
67 long tide-gauge records along the Indian coast (Supplementary Table S1). This underscores that
68 sea-level trends are time-scale dependent, and can be influenced by stochastic processes that tend
69 to decrease in magnitude with increasing time scale (Supplementary Information). Moreover, the
70 Indian tide gauges show good correlation with, and similar trends to, the tide gauges from the
71 Maldives for the overlapping interval since ~ 1990 CE (Fig. 1d; Supplementary Table S1). This
72 means that the tide gauges in India are informative of sea-level variability more broadly across the
73 region through time. Thus, the average rate of sea-level rise since 1807 CE reconstructed by Kench
74 et al.² in the Maldives from coral microatolls is faster than the quasi-centennial rates measured by
75 nearby tide gauges, and is too large to be understood in terms of large-scale climate alone.

76 To address the lack of near-continuous Common-Era sea-level reconstructions in the Indian
77 Ocean, Kench et al.² reconstructed sea level in the Maldives over the past two millennia using
78 fossil corals. We suggest that the 0.6–1.4-m centennial sea-level changes in the Maldives are too
79 large to have resulted from the thermal contraction and expansion of seawater related to large-scale
80 climate forcing alone. We quantify how exceptional ocean cooling or warming near the Maldives
81 would have been in a larger context were they sufficient to drive centennial sea-level trends as
82 large as those determined by Kench et al.². As Kench et al.² acknowledged, it is also unlikely
83 that these centennial sea-level changes reflect surface ice and water mass redistribution¹⁵, since

84 similar coeval changes are not supported by other intermediate- and far-field Common-Era sea level
85 reconstructions^{3,4}. We hypothesize that local-scale processes probably drove the apparent sea-level
86 lowstands in the Maldives. One possibility is that the corals used to reconstruct sea level sustained
87 erosion, which could render them biased (low) recorders of sea level (Supplementary Information).
88 Images of example corals from the Maldives shown by Kench et al.² (ref. 2, Supplementary Fig. 3)
89 feature planar surfaces without concentric growth rings, which may indicate erosion. If the corals
90 used for reconstructing sea level in the Maldives were eroded, then sea-level variability, radiative
91 forcing, and ocean physics could be reconciled, suggesting that the records of Kench et al.² should
92 not be interpreted as a Common-Era precedent for modern rates of sea-level rise related to climate.
93 More proxy reconstructions from the Maldives and the wider tropical Indian Ocean are necessary to
94 replicate the Maldives sea-level reconstruction, and more comprehensively quantify local, regional,
95 and global changes in sea level during the Common Era.

96 **References**

- 98 1. Kemp, A. C. et al. Paleo constraints on future sea-level rise. *Curr. Clim. Change Rep.*, **1**, 205–
99 215 (2015).
- 100 2. Kench, P. S. et al. Climate-forced sea-level lowstands in the Indian Ocean during the last two
101 millennia. *Nat. Geosci.*, **13**, 61–64 (2020).
- 102 3. Kemp, A. C. et al. Climate related sea-level variations over the past two millennia. *P. Natl.*
103 *Acad. Sci. U.S.A.*, **108**(27), 11017–11022 (2011).

- 104 4. Kopp, R. E. et al. Temperature-driven global sea-level variability in the Common Era. *P. Natl.*
105 *Acad. Sci. U.S.A.*, **113**(11), E1434–E1441 (2016).
- 106 5. Steinhilber, F. et al. Total solar irradiance during the Holocene. *Geophys. Res. Lett.*, **36**, L19704
107 (2009).
- 108 6. Sigl, M. et al. Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*,
109 **523**, 543–549 (2015).
- 110 7. Church, J. A. et al. Significant decadal-scale impact of volcanic eruptions on sea level and ocean
111 heat content. *Nature*, **438**, 74–77 (2005).
- 112 8. Gleckler, P. J. et al. Krakatoa lives: The effect of volcanic eruptions on ocean heat content and
113 thermal expansion. *Geophys. Res. Lett.*, **33**, L17702 (2006).
- 114 9. Cheng, L. et al. How fast are the oceans warming? *Science*, **363**, 128–129 (2019).
- 115 10. Zanna, L., et al. Global reconstruction of historical ocean heat storage and transport. *P. Natl.*
116 *Acad. Sci. U.S.A.*, **116**(4), 1126–1131 (2019).
- 117 11. Gebbie, G., & Huybers, P. The Little Ice Age and 20th-century deep Pacific cooling. *Science*,
118 **363**, 70–74 (2019).
- 119 12. Gebbie, G., & Huybers, P. The mean age of ocean waters inferred from radiocarbon observa-
120 tions: sensitivity to surface sources and accounting for mixing histories. *J. Phys. Oceanogr.*, **42**,
121 291–305 (2012).

122 13. Emile-Geay, J. et al. A global multiproxy database for temperature reconstructions of the
123 Common Era. *Sci. Data*, **4**, 170088 (2017).

124 14. Holgate, S. J. et al. New data systems and products at the permanent service for mean sea
125 level. *J. Coastal Res.*, **29**(3), 493–504 (2013).

126 15. Tamisiea, M. E., & Mitrovica, J. X. The moving boundaries of sea level change: understanding
127 the origins of geographic variability. *Oceanography*, **24**(2), 24–39 (2011).

128 **Supplementary Information** is linked to the online version of the paper at www.nature.com/ngeo.

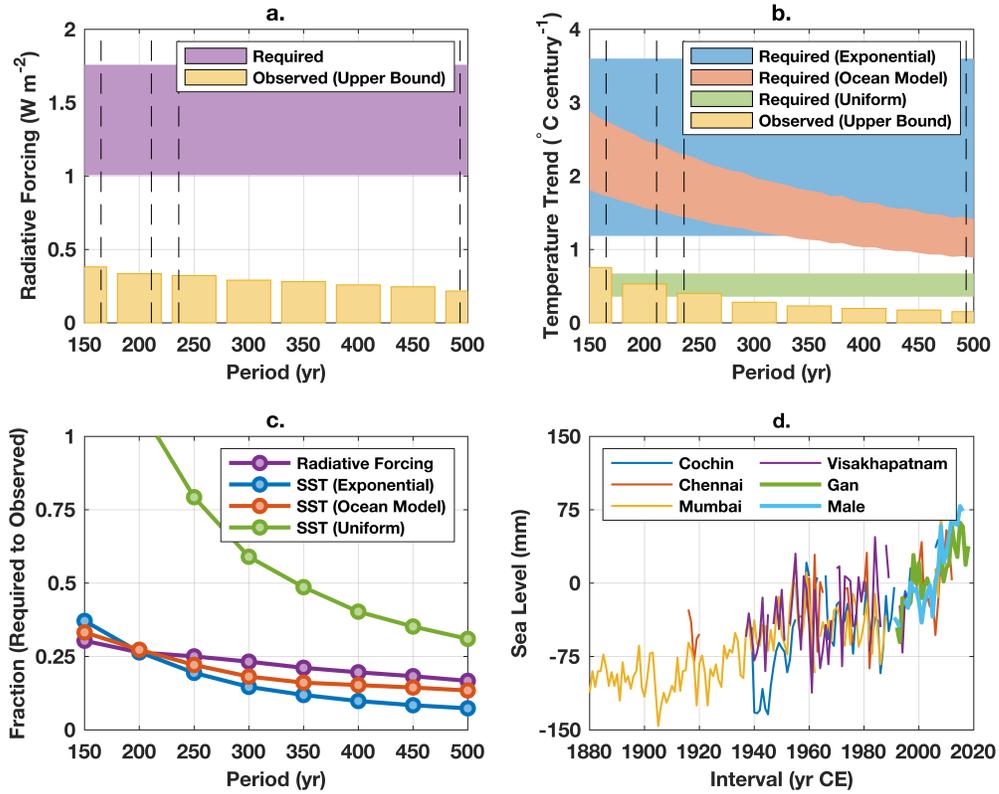
129 **Acknowledgments** CGP acknowledges support from NSF grant OCE-2002485, The Andrew W. Mellon
130 Foundation Endowed Fund for Innovative Research and The Joint Initiative Awards Fund from the Andrew
131 W. Mellon Foundation at the Woods Hole Oceanographic Institution. GG acknowledges support from NSF
132 grant OCE-1760958. AM acknowledges support from the National Research Foundation Singapore and
133 the Singapore Ministry of Education under the Research Centres of Excellence initiative, and also from the
134 National Research Foundation Singapore under its NRF Fellowship scheme (Award NRF-NRFF11-2019-
135 0008). We thank Paul Kench for helpful conversations on an earlier version of the manuscript.

136 **Author Contributions** CGP, ACK, and GG conceived of the study. All of the authors designed methods
137 and analyzed data. CGP wrote the manuscript with input from ACK, GG, and AJM.

138 **Competing Interests** The authors declare that they have no competing financial interests.

139 **Correspondence** Correspondence and requests should be addressed to CGP (cpiecuch@whoi.edu).

140 **Data Availability** Temperature-sensitive Common-Era proxy records from the PAGES2k project¹³ were
141 taken from the current data version available from the National Climatic Data Center website on 22 Jan 2020
142 (www1.ncdc.noaa.gov/pub/data/paleo/pages2k/pages2k-temperature-v2-2017/),
143 Only low-resolution oceanic data (“O2kLR”) covering most of the Common Era in the study area were used.
144 Numerical codes for the circulation model from Gebbie and Huybers¹² are available for download from GG’s
145 website (<https://www2.whoi.edu/staff/ggebbie/>). Total solar irradiance during the Holocene
146 from Steinhilber et al.⁵ was downloaded from the National Climatic Data Center FTP server on 3 Feb 2020
147 (ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/). The
148 estimates of volcanic aerosol forcing from Sigl et al.⁶ are as provided in the online version of the paper as
149 of 3 Feb 2020 (<https://www.nature.com/articles/nature14565>). The tide-gauge sea-level
150 data were extracted from the Permanent Service for Mean Sea Level (PSMSL) database¹⁴ on 24 Feb 2020
151 (<https://www.psmsl.org/data/obtaining/>).



152

153 **Figure 1. a**, Net surface heat flux required to generate a trend in thermosteric sea level (TSL) of
 154 $2.7\text{--}4.3\text{ mm yr}^{-1}$ (purple shading) exceeds the radiative-forcing magnitudes that likely took place
 155 during 0–1800 CE on time scales of 150–500 yr (yellow bars; see Supplementary Information).
 156 Dashed vertical black lines indicate the duration of sea-level trends reconstructed by Kench et al.²
 157 for the Maldives (corresponding to –91 to 401, 552 to 717, 1521 to 1757, and 1807 to 2018 CE).
 158 **b**, Sea-surface-temperature (SST) trends needed to generate a trend in TSL of $2.7\text{--}4.3\text{ mm yr}^{-1}$ for
 159 150–500 yr based on the assumption that ocean temperature trends decay exponentially with ocean
 160 depth (blue shading) and from an empirical ocean circulation model¹² (orange shading) exceed the
 161 SST trends that likely took place during 0–1800 CE on time scales of 150–500 yr (yellow bars;

162 see Supplementary Information). Only in the unrealistic case of assumed vertically uniform ocean
163 heat storage do the SST trends needed for TSL trends of $2.7\text{--}4.3\text{ mm yr}^{-1}$ (green shading) overlap
164 with the likely proxy-observed values, and then only for periods $< 300\text{ yr}$. Dashed vertical black
165 lines are as in **a**. **c**, Radiative-forcing magnitudes and SST trends that took place over 0–1800 CE
166 on time scales of 150–500 yr likely represent only a fraction (vertical axis) of the changes needed
167 to produce TSL trends of $2.7\text{--}4.3\text{ mm yr}^{-1}$ (Supplementary Information). **d**, Tide-gauge sea-level
168 records¹⁴ from India (Cochin, Chennai, Mumbai, Visakhapatnam) are correlated with data records
169 from the Maldives (Gan, Male) for the overlapping interval since ~ 1990 . The records from India
170 show longterm trends of $0.6\text{--}1.5\text{ mm yr}^{-1}$, which is smaller than the value of 4.2 mm yr^{-1} reported
171 by Kench et al.² for the Maldives between 1807–2018 CE using coral microatolls. Tide-gauge time
172 series are centered on their average value during 1990–2013 CE.

173 **Supplementary Information**

174 **Calculation of equivalent surface heat flux** Heat conservation and hydrostatic balance together
175 dictate that a net surface heat flux Q effects a change in thermosteric sea level (TSL) h_T following,

$$\dot{h}_T = \frac{\alpha}{c_p \rho_0} Q, \quad (1)$$

176 where dot is time derivative, α thermal expansion coefficient, c_p specific heat capacity of seawater,
177 and ρ_0 density of seawater. Rearranging to solve for Q gives,

$$Q = \frac{c_p \rho_0}{\alpha} \dot{h}_T. \quad (2)$$

178 Values of 1.0–1.8 W m⁻² quoted in the main text and shown in Fig. 1a are minimum and maximum
179 values computed from Eq. (2) using $\dot{h}_T \in \{2.7, 4.3\}$ mm yr⁻¹ and $\alpha \in \{3.1, 3.4\} \times 10^{-4}$ °C⁻¹.
180 We use representative values of $c_p = 4 \times 10^3$ J kg⁻¹ °C⁻¹ and $\rho_0 = 1 \times 10^3$ kg m⁻³.

181 Note that this formulation is in terms of a *net* heat flux Q , and does not explicitly account
182 for any damping effects¹⁶. As such, Q values computed here should be interpreted as the *minimum*
183 radiative-forcing anomaly needed to generate a given TSL trend. In other words, ratios of observed
184 to required radiative forcing (purple curve in Fig. 1c; see below) are conservative in the sense that
185 they represent upper bounds.

186 **Calculation of centennial anomalies in radiative forcing based on proxies** To estimate radiative
187 forcing, we summed together the 40-yr running-mean total solar irradiance values from Steinhilber
188 et al.⁵ (linearly interpolated onto a yearly spacing) and annual atmospheric aerosol loading owing to
189 volcanic eruptions determined by Sigl et al.⁶ (zero values were imputed for years without volcanic

190 eruptions) and removed the time average over the interval 0–1800 CE (Supplementary Fig. S1a–c).
 191 We computed running averages of the reconstructed radiative-forcing anomaly series for averaging
 192 periods between 150 and 500 yr in 50-yr increments (Supplementary Fig. S1d). With each of these
 193 running-average time series, we computed absolute values and evaluated the 95th percentile of the
 194 resulting time-smoothed radiative-forcing anomaly magnitude record (Supplementary Fig. S1e–f).
 195 These 95th percentiles (yellow bars in Fig. 1a) reflect upper bounds on the radiative forcing values
 196 at a given time scale (i.e., 95% of values are smaller than this). Implicit in our analysis, following
 197 ref. 2, is the assumption that this global forcing applies over the central equatorial Indian Ocean.

198 To quantify, in a relative sense, to what extent the reconstructed radiative-forcing anomalies
 199 were sufficient to generate TSL trends as large as the trends inferred in the Maldives², we evaluated
 200 the ratio of the reconstructed radiative-forcing anomaly as a function of time scale (Supplementary
 201 Fig. S1e–f) to the required radiative forcing estimated using Equation 2 (purple shading in Fig. 1a,
 202 assumed to be a uniform distribution) and took 95th percentiles, giving the purple values shown in
 203 Fig. 1c (cf. discussion below related to a similar calculation for SST trends).

204 **Calculation of the implied sea-surface-temperature (SST) trend** Trends in TSL \dot{h}_T are related
 205 to ocean temperature trends $\dot{T}(z)$ according to,

$$\dot{h}_T = \int_{-H}^0 \alpha \dot{T}(z) dz, \quad (3)$$

206 where z is the vertical coordinate (positive upwards) and H the ocean depth. In the scaling analysis,
 207 we assumed that,

$$\dot{T}(z) = \dot{T}_0 \exp(z/H_T). \quad (4)$$

208 Integrating and rearranging, we obtain the analytical solution for \dot{T}_0 , which is the SST trend,

$$\dot{T}_0 = \frac{\dot{h}_T}{\alpha H_T} [1 - \exp(-H/H_T)]^{-1}. \quad (5)$$

209 Values of 1.2–3.6 °C century⁻¹ in the main text are the minimum and maximum values computed
210 from Eq. (5) using $\dot{h}_T \in \{2.7, 4.3\}$ mm yr⁻¹, $\alpha \in \{1.6, 1.9\} \times 10^{-4}$ °C⁻¹, $H_T \in \{750, 1250\}$ m,
211 and $H = 4 \times 10^3$ m (cf. blue shading in Fig. 1b).

212 Assuming instead that \dot{T} is vertically uniform, Eq. (5) reduces to the simplified form,

$$\dot{T}_0 = \frac{\dot{h}_T}{\alpha H} \quad (6)$$

213 Evaluating this equation using the same parameter values, and taking the minimum and maximum,
214 we obtain the green shading in Fig. 1b.

215 **Choice of e -folding depth scale** We chose a range of 750–1250 m for the e -folding scale H_T of
216 ocean temperature changes. This choice was motivated by published estimates^{10,11} of global-ocean
217 heat storage during the past 140–270 yr. The reconstruction of Zanna et al.¹⁰ suggests that $\sim 75\%$
218 of global ocean heat storage since 1871 occurred in the upper 700 m and $\sim 95\%$ in the top 2000
219 m (their Fig. 1a–1c). The model simulation of Gebbie and Huybers¹¹ calculated from equilibrium
220 at 1750 CE shows that $\sim 50\%$ and $\sim 85\%$ of the ocean heat content changes occurred at depths
221 above 700 and 2000 m, respectively (their Fig. 4b). Since the 140–270-yr time scales highlighted
222 in these studies^{10,11} are on the short end of the 150–500-yr range considered here², we selected
223 750–1250 m for the e -folding depth scale as conservative values that allow comparatively more
224 heat to penetrate the deep ocean, requiring a smaller change in SST to achieve a given TSL trend.

225 **Circulation model calculations** We run the circulation model from Gebbie and Huybers¹² with
226 idealized concentration (Dirichlet) boundary conditions. We perform 100 iterations of a 40,000-yr
227 simulation with randomized phasing of the boundary conditions. Surface boundary conditions are
228 globally uniform and follow a frequency spectrum with a power law of -1.64 following Huybers
229 and Curry¹⁷. We use the global Green's function (or transit-time distribution) to produce simulated
230 time series, and results are similar if we use four surface patches to account for climate hemispheric
231 asymmetries. We consider non-overlapping intervals of between 150 and 500 yr (10-yr increments)
232 and compute SST and TSL trends within the equatorial Indian Ocean near the Maldives (4°N 78°E ;
233 3750-m depth). For each trend window, we fit a first-order least-squares trend line to all TSL-SST
234 trend pairs (Supplementary Fig. S2). The slope of this fit was taken to be the SST change per unit
235 change in TSL for a particular time scale. For example, we found that a trend of 1 mm yr^{-1} in TSL
236 corresponds to a SST trend of 0.67 and $0.33\text{ }^{\circ}\text{C century}^{-1}$ at respective time scales of 150 and 500
237 yr. Slopes are multiplied by $2.7\text{--}4.3\text{ mm yr}^{-1}$ to produce the orange-shaded region in Fig. 1b.

238 **Calculation of centennial SST trends from temperature-sensitive proxy data** We analyzed all
239 Common-Era SST proxy reconstructions from the PAGES2k consortium¹³ from the Indian Ocean
240 and around the Indonesian Throughflow (see Data Availability). This data set comprises one record
241 each from the Arabian Sea, Horn of Africa, southwest coast of India, the Philippines, South China
242 Sea, and western equatorial Pacific, and four in Makassar Strait (Supplementary Figs. S3, S4a–j).
243 We linearly interpolated each available record onto a common yearly interval, and then computed
244 trends from each record for every 150- to 500-yr period between 0–1800 CE. This procedure gave
245 a separate time series with all possible trends across the ten proxy locations for each trend period

246 between 150 and 500 yr. With each period-specific trend time series, we removed the overall mean,
247 took absolute values, and then computed the 95th percentile of these anomalous trend magnitudes
248 (Supplementary Fig. S4k–l). These 95th percentiles (yellow bars in Fig. 1b) reflect upper bounds
249 on the proxy SST trends at a given time scale (i.e., 95% of trends are smaller than these values).

250 Note that these SST proxies are not from the Maldives and thus are not truly collocated with
251 the sea-level reconstruction from Kench et al.². Our approach follows that of Kench et al.² in that
252 we use available SST proxy records from nearby locations to interpret the sea-level reconstruction
253 from the Maldives, where “nearby” is taken to mean “in the Indian Ocean or around the Indonesian
254 Throughflow.” However, we consider more SST records than do Kench et al.², including a record
255 from the southwest coast of India, which is < 1,000 km from the sea-level reconstruction in the
256 Maldives (Supplementary Fig. S3). Our calculations should thus be interpreted as spanning a
257 plausible envelope of possible SST trends (as a function of time scale) across the tropical Indian
258 Ocean during the Common Era. We believe that the true Common-Era SST history in the Maldives
259 is within this realistic range. In other words, our results quantify how unusual the SST trends in
260 the Maldives would have been, within a larger regional context, to be large enough to drive the
261 sea-level trends inferred by Kench et al.².

262 As with radiative forcing, we quantified the relative extent to which reconstructed SST trends
263 were large enough to generate TSL trends as large as those in the sea-level reconstruction from the
264 Maldives². We evaluated the ratio of the amplitudes of reconstructed SST trends (Supplementary
265 Fig. S4k–l) to the required SST trends using Equations 5 and 6 and from the empirical circulation

266 model¹² (blue, green, and orange shading in Fig. 1b, respectively, which we assumed were uniform
267 distributions) and took the 95th percentiles as a function of time scale. This method produced the
268 respective blue, green, and orange values in Fig. 1c.

269 **Instrumental tide-gauge sea-level data** To interpret the most recent (1807–2018 CE) sea-level
270 trend for the Maldives from Kench et al.², we used tide-gauge annual-mean sea-level records from
271 the Permanent Service for Mean Sea Level¹⁴ (see Data Availability). We used all > 70-yr records
272 in the database from along coastal India (four time series) and from the Maldives (two time series).
273 For all records, we computed best estimates of least-squares trends to the available data, ignoring
274 data gaps. The trend values are given in Supplementary Table S1. Note that we did not consider
275 the long (82-yr) tide-gauge record from Garden Reach, India, since it is located far upstream in the
276 Bhāgirathi-Hooghly, near Kolkata, and is not reflective of large-scale, open-ocean conditions.

277 The sea-level trends from tide-gauge data quoted in the main text (Supplementary Table S1)
278 were computed over the full record lengths of the respective time series. To quantify the sensitivity
279 of the trends to time scale, we computed trends in the tide-gauge data for all possible time intervals
280 ≥ 20 yr using the longest and most continuous records from Visakhapatnam, Mumbai, and Cochin
281 (Supplementary Fig. S5). While larger trends are possible and observed in the tide-gauge data over
282 shorter periods (e.g., trends of 4–7 mm yr⁻¹ over periods of 20–30 yr), trends over longer intervals
283 have smaller amplitudes (e.g., $\lesssim 3$ mm yr⁻¹ for $\gtrsim 40$ -yr periods). Trends as large and sustained as
284 those reported by Kench et al.² in the Maldives during 1807–2018 CE (~ 4 mm yr⁻¹) are therefore
285 not supported by a more general, in-depth analysis of the tide-gauge data.

286 **Interpretation of corals** A microatoll is a coral colony with a living outer margin, but with a
287 dead upper surface. Microatolls typically form concentric rings on their upper surfaces related to
288 interannual variability in lowest water levels and highest levels of survival²⁶. A microatoll growing
289 during decadal periods of stable sea level will record little net elevation change from its center to
290 its outer perimeter, even as concentric rings grow up and die down over shorter periods. If sea
291 level rises or falls during the lifetime of a microatoll, its outer perimeter will be higher or lower,
292 respectively, than its center. After a microatoll dies, this concentric ring morphology remains
293 recognizable unless the coral's upper surface experiences substantial erosion (e.g., ref. 27, Fig. 6).
294 Corals that remain in the intertidal zone for extended periods of time after death can sustain intense
295 bioerosion²⁸.

296 Most of the fossil corals in the photographs from Mahutigalaa (ref. 2, Supplementary Fig. 3)
297 exhibit flat upper surfaces. They show no clear elevation changes from their centers to their outer
298 perimeters. If these corals are uneroded, then this morphology indicates that sea levels were stable
299 during coral growth. However, if there was rapid sea-level change during the lifetimes of the corals,
300 some of them would be expected to show much higher or lower outer perimeters compared to their
301 centers. If each coral is flat and uneroded but has a different elevation, it would imply that sea level
302 was stable over long periods as each coral grew, with punctuated sea-level changes limited to short
303 intervals from which no microatolls are preserved. Alternatively, the flat tops of the corals could
304 plausibly be explained by erosion, such that each coral was planed off at a level below its original
305 height of living coral. In that case, the coral would reflect a limiting (minimum) data point, and the
306 true sea level could have been higher.

307 In addition to the lack of net elevation gain or loss exhibited by any of the Mahutigalaa
308 corals, most of the corals look to have smooth, planar surfaces, and there is no clear evidence of
309 concentric rings. This also suggests erosion of the corals. For groups of roughly coeval corals
310 in their data set, Kench et al.² discarded the higher corals as outliers, suggesting that their higher
311 elevations resulted from ponding. Instead, we propose that the lower corals from each group may
312 have been more eroded. Kench et al.² based their reconstruction on the lower, possibly planed-off
313 corals. But, if the higher fossil corals provide the best estimate of sea level in the Maldives at any
314 particular time, then sea level during the lowstands reported by Kench et al.² may never have fallen
315 lower than 0.4–0.5 m below current sea level in 2018 CE.

316 **Additional References**

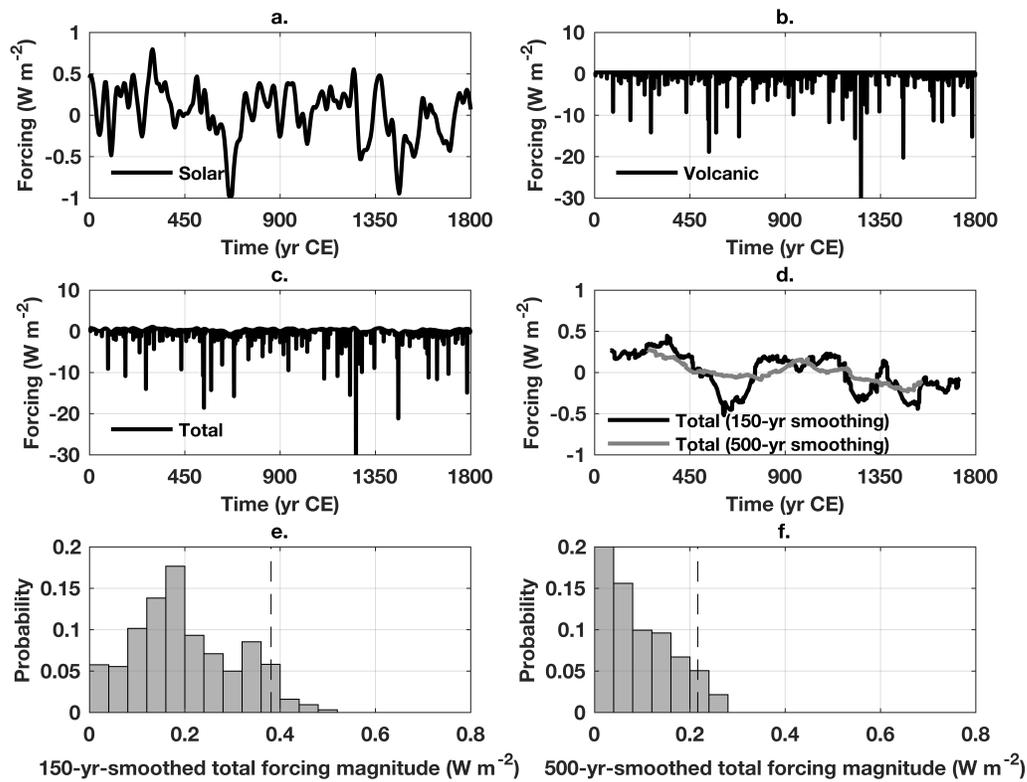
- 318 16. Douglass, D. H. & Knox, R. S. Climate forcing by the volcanic eruption of Mount Pinatubo.
319 *Geophys. Res. Lett.*, **32**, L05710 (2005).
- 320 17. Huybers, P. & Curry, W. Links between annual, Milankovitch and continuum temperature
321 variability. *Nature*, **441**, 329–332 (2006).
- 322 18. Tierney, J. E. et al. Past and future rainfall in the Horn of Africa. *Sci. Adv.*, **1**(9), e1500682
323 (2015).
- 324 19. Doose-Rolinski, H. et al. High-resolution temperature and evaporation changes during the Late
325 Holocene in the northeastern Arabian Sea. *Paleoceanography*, **16**(4), 358–367 (2001).

- 326 20. Saraswat, R. et al. Deglaciation in the tropical Indian Ocean driven by interplay between the
327 regional monsoon and global teleconnection. *Earth Planet. Sc. Lett.*, **375**, 166–175 (2013).
- 328 21. Zhao, M. et al. A millennial-scale $U_{37}^{K'}$ sea-surface temperature record from the South China
329 Sea (8°N) over the last 150 kyr: Monsoon and sea-level influence. *Palaeogeogr. Palaeocl.*,
330 **236**(1–2), 39–55 (2006).
- 331 22. Linsley, B. K. et al. Holocene evolution of the Indonesian throughflow and the western Pacific
332 warm pool. *Nat. Geosci.*, **3**, 578–583 (2010).
- 333 23. Newton, A. et al. Changes in the Indonesian Throughflow during the past 2000 yr. *Geology*,
334 **39**(1), 63–66 (2011).
- 335 24. Oppo, D. W. et al. 2,000-year-long temperature and hydrology reconstructions from the Indo-
336 Pacific warm pool. *Nature*, **460**, 1113–1116 (2009).
- 337 25. Stott, L. et al. Southern Hemisphere and Deep-Sea Warming Led Deglacial Atmospheric CO₂
338 Rise and Tropical Warming. *Science*, **318**(5849), 435–438 (2007).
- 339 26. Meltzner, A. J., & Woodroffe, C. D. Coral microatolls, in *Handbook of Sea-Level Research*,
340 Shennan, I. et al. (Editors), John Wiley & Sons, Chichester, UK, pp. 125–145 (2015).
- 341 27. Majewski, J. M. et al. Holocene relative sea-level records from coral microatolls in Western
342 Borneo, South China Sea. *The Holocene*, **28**(9), 1431–1442 (2018).

343 28. Taylor, F. W. et al. Analysis of partially emerged corals and reef terraces in the central Van-
344 uatu Arc: Comparison of contemporary coseismic and nonseismic with Quaternary vertical
345 movements. *J. Geophys. Res.*, **92**, 4905–4933 (1987).

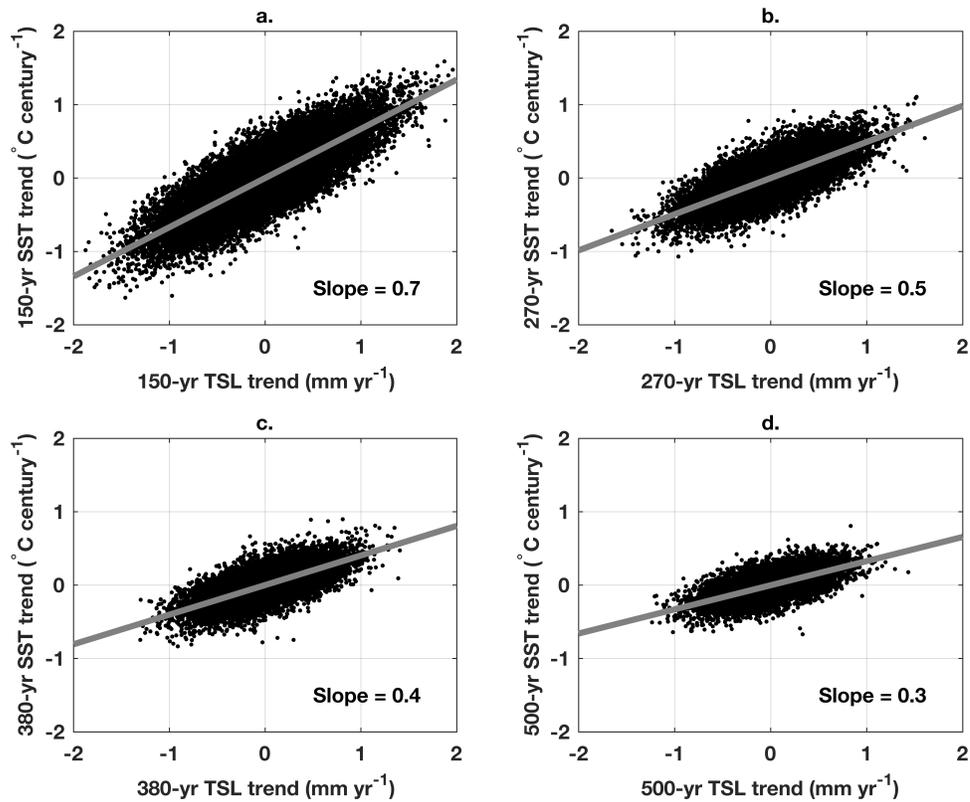
Location	Lat (°N)	Lon (°E)	Trend (mm yr ⁻¹)	Length (yr)
Chennai, India	13	80	0.57 (1.87)	1916–2015
Visakhapatnam, India	18	83	0.92 (3.95)	1937–2013
Mumbai, India	19	73	0.84 (4.21)	1878–2015
Cochin, India	10	76	1.51 (3.23)	1939–2013
Gan, Maldives	−1	73	3.21	1989–2018
Male, Maldives	4	74	4.70	1991–2016

Supplementary Table S1. Names, locations, and record lengths of tide-gauge sea-level records used here. The trend is the best estimate of the slope of a least-squares linear fit to the available data (ignoring any data gaps). Parenthetical values for Indian tide gauges (Chennai, Visakhapatnam, Mumbai, Cochin) are trends since 1990 for direct comparison with the trends from the Maldivian gauges (Gan, Male).



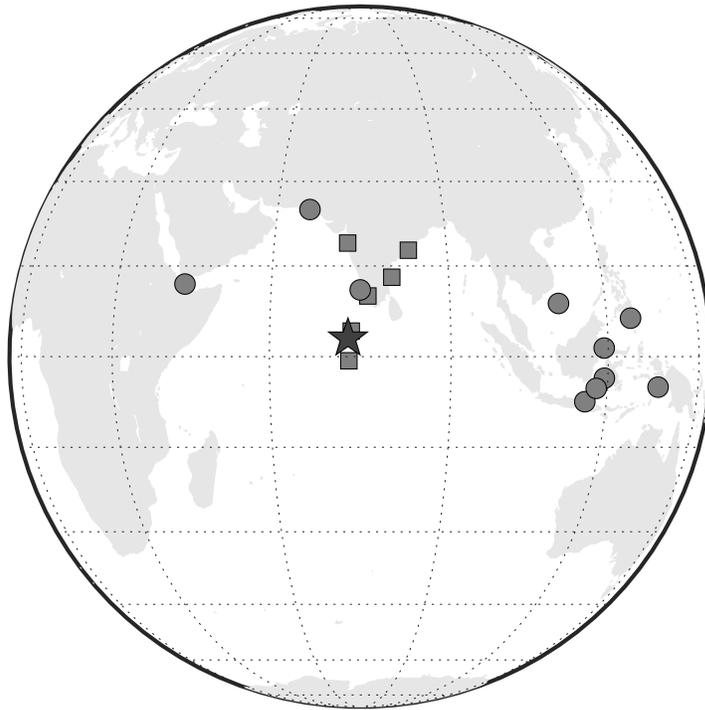
346

347 **Supplementary Figure S1.** **a**, Solar irradiance from Steinhilber et al.⁵. **b**, Volcanic aerosol forcing
 348 from Sigl et al.⁶. **c**, Total radiative forcing (sum of time series from panels **a** and **b**). **d**, Smoothed
 349 radiative forcing (time series from panel **c** with a 150- and 500-yr running-mean smoother applied).
 350 Mean values during 0–1800 CE are removed from the time series in panels **a–d**. **e**, Histogram of
 351 150-yr-smoothed forcing amplitudes from panel **d**. Black dashed vertical line is the 95th percentile.
 352 **f**, As in **e** but for 500-yr-smoothed values.



353

354 **Supplementary Figure S2.** **a**, Black dots are all pairs of 150-yr TSL and SST trends from the
 355 long empirical circulation model integrations. Gray line is a trend line fit to the scatter, where the
 356 slope (indicated to the bottom right) is the change in SST trend per unit change in TSL trend in
 357 units of (°C century⁻¹)/(mm yr⁻¹). **b–d**, As in **a** but for periods of **b**, 270 yr, **c**, 380 yr, and **d**,
 358 500 yr. Longer periods permit a more vertically homogeneous temperature response.

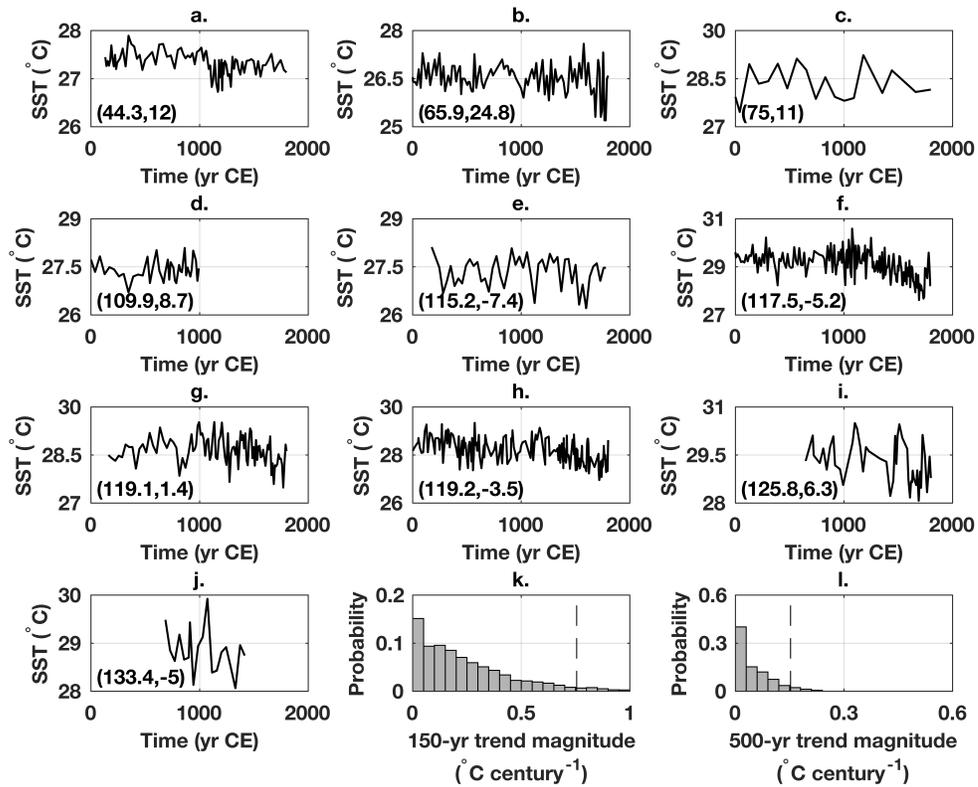


359

360 **Supplementary Figure S3.** Locations of proxy and instrumental data assets used in this study.

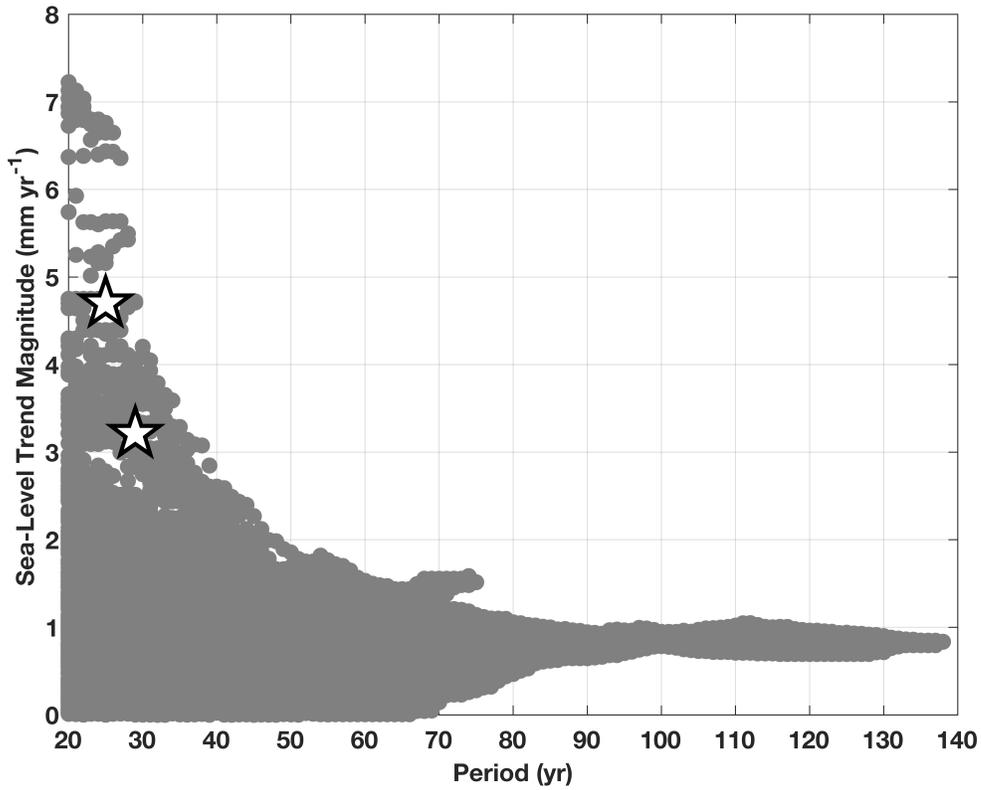
361 Dark gray star is the location of the sea-level reconstruction from the Maldives. Light gray circles

362 and squares are, respectively, are the locations of SST proxies and tide-gauge sea-level records.



363

364 **Supplementary Figure S4.** Common-Era proxy SST reconstructions from **a**, Horn of Africa¹⁸,
 365 **b**, Arabian Sea¹⁹, **c**, southwest coast of India²⁰, **d**, South China Sea²¹, **e–h**, Makassar Strait^{22–24},
 366 **i**, Philippines²⁵, and **j**, western equatorial Pacific²⁵. Longitude (°E) and latitude (°N) are given in
 367 parenthesis at bottom left. Histograms of anomalous SST trend amplitudes across all ten sites for
 368 **k**, 150-yr and **l**, 500-yr periods. Black dashed vertical lines are 95th percentiles of the distributions.



369

370 **Supplementary Figure S5.** Relative sea-level trends computed over all possible time periods from
371 the longer Indian tide-gauge records at Visakhapatnam, Mumbai, and Cochin, shown as a function
372 of period. Stars indicate sea-level trends computed from the shorter Maldivian tide-gauge records
373 at Gan and Male (cf. Supplementary Table S1).