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Climate did not drive Common Era Maldivian sea-level lowstands

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Reconstructions of Common Era sea level are informative of relationships between sea level and natural climate variability, and the uniqueness of modern sea-level rise[1]. Kench et al.[2] recently reconstructed Common Era sea level in the Maldives, Indian Ocean, using corals, and reported periods of 150–500 years when sea level fell and rose at average rates of 2.7–4.3 mm yr^{-1}, which they attributed to ocean cooling and warming inferred from reconstructions of sea-surface temperature (SST) and radiative forcing (Fig. 2 of ref. [2]). We challenge their interpretation, using 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 Maldives[2]. Our results support the paradigm that modern rates and magnitudes of sea-level rise due to climate change are unprecedented during the Common Era[3,4].

Radiative forcing (for example, related to solar activity[5] and volcanic eruptions[6]) varies over a broad range of timescales, and influences global climate and sea level[7,8]. For example, models show that major volcanic eruptions during the twentieth century drove rapid interannual falls in global-mean sea level (on the order of millimetres per year) that were followed by gradual decadal rises (on the order of tenths of millimetres per year) as the climate system recovered[7]. To determine whether variability in radiative forcing on centennial and longer timescales in the Common Era was sufficient to drive TSL trends as large and sustained as those inferred for the Maldives[2], we express trends in TSL in terms of their equivalent net surface heat flux (see Supplementary Information; unless otherwise indicated, 'trend' indicates an average rate of change). Using a thermal expansion coefficient characteristic of tropical surface ocean waters (3.1–3.4 × 10^{-4} °C^{-1}), we estimate that a net flux of 1.0–1.8 W m^{-2} is required for a TSL trend of 2.7–4.3 mm yr^{-1}. The required flux is stronger than centennial-scale variations in reconstructions of radiative forcing[5,6], which can be uncertain, but exhibit magnitudes < 0.3 and < 0.1 W m^{-2} over timescales of 150 and 500 years, respectively (95% confidence; Fig. 1a and Supplementary Information). Therefore, radiative forcing probably accounts for < 19% (< 8%) of the forcing required to produce 150-year (500-year) TSL trends of 2.7–4.3 mm yr^{-1} (Fig. 1c, purple).

We also estimate what SST trend is required to generate a given trend in TSL (Supplementary Information). We assume that magnitudes of ocean temperature changes decay exponentially from the surface to the bottom over an *e*-folding depth scale of 750–1,250 m. This translates to 45–61% (83–94%) of ocean heat storage occurring in the upper 700 m (2,000 m), similar to estimates from model-data syntheses[9,10] of changes in global ocean heat content over the past 140–270 years. Using a reasonable global-ocean, volume-averaged thermal expansion coefficient (1.6–1.9 × 10^{-4} °C^{-1}), we find that TSL trends of 2.7–4.3 mm yr^{-1} require attendant SST trends of 1.2–3.6 °C per century (Fig. 1b). This estimate is supported by long integrations of an empirical ocean circulation model[11], which suggest that TSL trends of 2.7–4.3 mm yr^{-1} sustained for 150 and 500 years require SST trends of 1.8–2.9 and 0.9–1.4 °C per century, respectively (Fig. 1b and Supplementary Information). These model results are consistent with the basic expectation that, on longer timescales under sustained climate forcing, relatively more heat penetrates the deep ocean, requiring a comparatively smaller SST change to produce a given TSL trend.

The required SST trends are larger than observed in ten reconstructions of Common Era SST[12] in the Indian Ocean and Indonesian Throughflow, which show trends of < 0.8 and < 0.2 °C per century on timescales of 150 and 500 years, respectively (95% confidence; Fig. 1b and Supplementary Information). Although they are not from the Maldives, these SST reconstructions are informative of the range of reconstructed centennial SST trends over the tropical Indian Ocean during the Common Era. We find that SST reconstructions probably account for < 37% and < 7% of the temperature trends needed to explain TSL trends of 2.7–4.3 mm yr^{-1} on timescales of 150 and 500 years, respectively, assuming exponential vertical structure (Fig. 1c, blue). Using the empirical ocean circulation model, we estimate corresponding percentages of < 33% and < 13% (Fig. 1c, orange). Even making the extreme assumption that ocean temperature trends are vertically uniform, which is unrealistic given the long adjustment timescales in the deep ocean[11], we find that SST trends required for trends in TSL of 2.7–4.3 mm yr^{-1} (Fig. 1b) are generally larger than are inferred from SST reconstructions, especially for periods > 300 years (Fig. 1c, green).

Kench et al.[2] reconstructed a sea-level trend of 4.2 mm yr^{-1} in the Maldives for the modern industrial interval between 1807 and 2018 CE. Comparable trends of 3.2–4.7 mm yr^{-1} are seen in two tide-gauge sea-level records[13] in the Maldives for the past 25–30 years (Supplementary Table 1). However, smaller sea-level trends of 0.6–1.5 mm yr^{-1} are seen for the past 80–140 years in four long tide-gauge records along the Indian coast (Supplementary Table 1). This underscores that sea-level trends are timescale dependent and can be influenced by stochastic processes that tend to decrease in magnitude with increasing timescale (Supplementary Information). Moreover, the Indian tide gauges show good correlation with, and similar trends to, the tide gauges from the Maldives for the overlapping interval since ~1990 CE (Fig. 2 and Supplementary Table 1). This means that the tide gauges in India are informative of sea-level variability more broadly across the region through time. Thus, the

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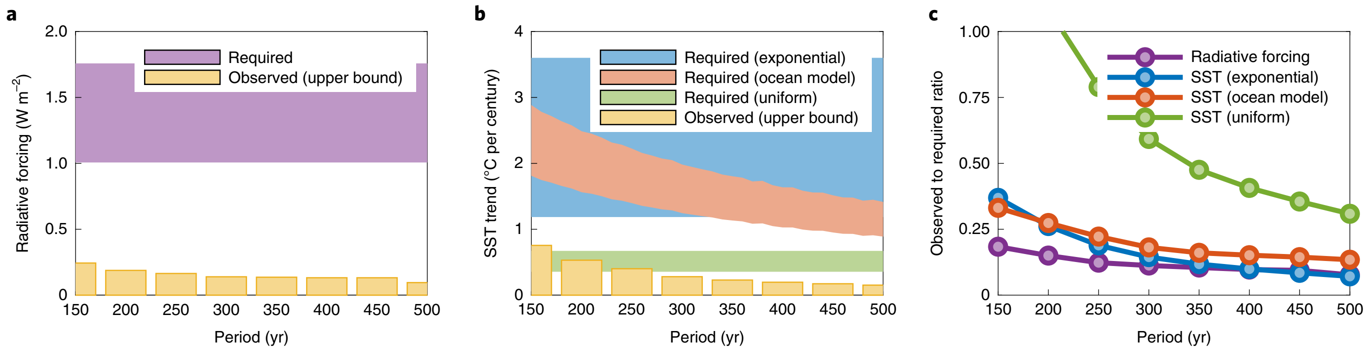

Fig. 1 | Pre-industrial radiative forcing and SST changes. a, Surface heat flux required for TSL trends of 2.7–4.3 mm yr^{-1} (purple) exceeds radiative forcing magnitudes during 0–1800 CE on timescales of 150–500 years (yellow; Supplementary Information). **b**, SST trends needed for TSL trends of 2.7–4.3 mm yr^{-1} assuming ocean temperature trends decay exponentially with depth (blue) and an empirical model[11] (orange) exceed SST trends during 0–1800 CE on timescales of 150–500 years (yellow; Supplementary Information). For vertically uniform ocean heating, required SST trends (green) overlap with observed values only for timescales <300 years. **c**, Ratio of observed to required values from **a** and **b**. The model output used to create this figure can be found in Supplementary Data 1.

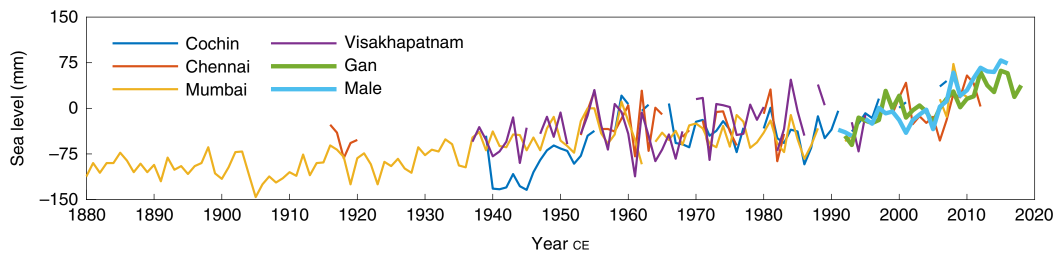

Fig. 2 | Post-industrial sea-level changes near the Maldives. Tide-gauge relative sea-level records[13] from India (Cochin, Chennai, Mumbai, Visakhapatnam) are correlated with those from the Maldives (Gan, Male) for the overlapping interval since ~1990 CE. The records from India show long-term trends of 0.6–1.5 mm yr^{-1}, which is smaller than the value of 4.2 mm yr^{-1} reported by Kench et al.[2] for the Maldives between 1807 and 2018 CE using coral microatolls. Tide-gauge time series are centred on their average value during 1990–2013 CE. For relative sea-level trends computed over all possible periods, see Supplementary Fig. 5.

average rate of sea-level rise since 1807 CE reconstructed by Kench et al.[2] in the Maldives from coral microatolls is faster than the quasi-centennial rates measured by nearby tide gauges.

To address a paucity of near-continuous Common Era sea-level reconstructions in the Indian Ocean, Kench et al.[2] reconstructed sea level in the Maldives over the past two millennia using fossil corals. We suggest that the 0.6–1.4-m centennial sea-level changes in the Maldives are too large to have resulted from the thermal contraction and expansion of seawater related to large-scale climate forcing alone. We quantify how exceptional ocean cooling or warming near the Maldives would have been in a larger context were they sufficient to drive centennial sea-level trends as large as those determined by Kench et al.[2]. We agree with Kench et al.[2] that it is also unlikely that these centennial sea-level changes reflect surface ice and water mass redistribution[14], as similar coeval changes are not supported by other intermediate- and far-field Common Era sea-level reconstructions[3,4]. We hypothesize that the corals used to reconstruct sea level experienced erosion, which could render them biased (low) sea-level recorders (Supplementary Information), effecting apparent sea-level lowstands. Images of example corals from the Maldives shown by Kench et al.[2] (Supplementary Fig. 3 of ref. [2]) feature planar surfaces without concentric growth rings, which may indicate erosion. If the corals used for reconstructing sea level in the Maldives were eroded, then sea-level variability, radiative forcing and ocean physics might be reconciled, suggesting that the records of Kench et al.[2] should not be interpreted as a Common Era precedent for modern rates of sea-level rise related to climate. More proxy reconstructions from the Maldives and the wider tropical Indian Ocean are necessary to replicate the Maldives sea-level reconstruction, and more comprehensively quantify local, regional and global changes in sea level during the Common Era.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-021-00731-2.

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Data availability

Temperature-sensitive Common Era proxy records from the PAGES2k project[12] were taken from the current data version available from the National Climatic Data Center website on 22 Jan 2020 (www1.ncdc.noaa.gov/pub/data/paleo/pages2k/pages2k-temperature-v2-2017/). Only low-resolution oceanic data ('O2kLR') covering most of the Common Era in the study area were used. Numerical codes for the circulation model from ref. [11] are available for download from G.G.'s website (https://www2.whoi.edu/staff/ggebbie/). Total solar irradiance during the Holocene from ref. [5] was downloaded from the National Climatic Data Center server on 3 Feb 2020 (https://www.ncei.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/steinhilber2009tsi.txt). The estimates of volcanic aerosol forcing from ref. [6] are as provided in the online version of the paper as of 3 Feb 2020 (https://doi.org/10.1038/nature14565). The tide-gauge sea-level data were extracted from the Permanent Service for Mean Sea Level database[13] on 24 Feb 2020 (https://www.psmsl.org/data/obtaining/). Source data are provided with this paper.

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Author contributions

C.G.P., A.C.K. and G.G. conceived the study. All of the authors designed methods and analysed data. C.G.P. wrote the manuscript with input from A.C.K., G.G. and A.J.M.

Competing interests

The authors declare no competing interests.

Additional information

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