Article:

Majewski, J.M., Meltzner, A.J., Switzer, A.D. et al. (9 more authors) (2022) Extending instrumental sea-level records using coral microatolls, an example from Southeast Asia. Geophysical Research Letters, 49 (4). e2021GL095710. ISSN 0094-8276

https://doi.org/10.1029/2021gl095710

ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095710

Key Points:

- Validating the coral microatoll technique to reconstruct relative sea level
- Producing 16 new sea-level index points from two microatolls between 1915 and 2012
- Extending the record of modern sea-level change by over 50 years and reducing its uncertainty by ~50%

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
J. M. Majewski,
jmmajewski@ntu.edu.sg

Citation:
Majewski, J. M., Meltzner, A. J., Switzer, A. D., Shaw, T. A., Li, T., Bradley, S., et al. (2022). Extending instrumental sea-level records using coral microatolls, an example from Southeast Asia. *Geophysical Research Letters*, *49*, e2021GL095710. https://doi.org/10.1029/2021GL095710

Received 17 AUG 2021
Accepted 22 NOV 2021

Extending Instrumental Sea-Level Records Using Coral Microatolls, an Example From Southeast Asia

J. M. Majewski[1], A. J. Meltzner[1,2], A. D. Switzer[1,2], T. A. Shaw[1], T. Li[1], S. Bradley[3], J. S. Walker[4,5], R. E. Kopp[4,5], D. Samanta[1], D. H. Natawidjaja[6], B. W. Suwargadi[6], and B. P. Horton[1,2]

[1]Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore, [2]Asian School of the Environment, Nanyang Technological University, Singapore, Singapore, [3]Department of Geography, University of Sheffield, Sheffield, UK, [4]Department of Earth & Planetary Sciences, Rutgers University, New Brunswick, NJ, USA, [5]Rutgers Institute of Earth, Ocean & Atmospheric Sciences, New Brunswick, NJ, USA, [6]Research Center for Geotechnology, Indonesian Institute of Sciences, Bandung, Indonesia

Abstract The small number of reliable long-term (i.e., >50 yrs) tide gauges in tropical locations is a major source of uncertainty in modern sea-level change. Coral microatolls record relative sea-level (RSL) change over their lifetimes and have the potential to extend the instrumental record. Here, we examined a 20th and 21st century RSL record from two living coral microatolls from Mapur Island, Indonesia, which produced 16 sea-level index points. We validated and combined the living coral microatoll data with tide gauge data to show RSL at Mapur Island was 0.0 ± 1.6 mm/yr (2σ) from 1915 to 1990 and 1.0 ± 2.1 mm/yr (2σ) from 1990 to 2019. Through the addition of microatoll RSL data we extended the record of modern sea-level change by over 50 years and reduced its uncertainty by ~50%.

Plain Language Summary Long instrumental sea-level records from tide-gauges are required to understand regional sea-level variability, but in most tropical regions tide-gauge records only began in the latter half of the 20th century. Therefore, there is considerable uncertainty in the regional sea-level projections in tropical regions, which are necessary for effective coastal risk management. Coral microatolls can extend the duration of tide-gauge records and provide completely new sea-level records because their growth patterns reveal important information about sea level during the coral's lifetime. In this study, we examined sea-level records from living coral microatolls from Mapur Island, Indonesia. We validated the coral microatoll technique to reconstruct sea level with data from the nearby Tanjong Pagar tide gauge in Singapore. The combined coral microatoll and tide gauge data showed sea level change of 0.0 ± 1.6 mm/yr (2σ) from 1915 to 1990 and 1.0 ± 2.1 mm/yr (2σ) from 1990 to 2019. Coral microatolls can extend sea level records for other tropical regions where tide gauges have only recently been installed and provide a new data source in locations where tide gauges have not and might not be installed.

1. Introduction

Anthropogenic climate change has caused global mean sea level (GMSL) to rise primarily through thermal expansion of the oceans, which increases ocean volume (e.g., Frederikse et al., 2020), and the melting of land-based ice, which increases ocean mass (e.g., Shepherd et al., 2018). Globally, tide-gauge records show GMSL rose 1.1–1.9 mm/yr over the 20th century (Dangendorf et al., 2019; Frederikse et al., 2020; Hay et al., 2015), a substantial increase over the rates of sea-level rise during the past few millennia (Kemp et al., 2018; Kopp et al., 2016; Walker et al., 2021).

Regional relative sea-level (RSL) can vary substantially from GMSL due to processes such as atmosphere and ocean dynamics (e.g., Tkalich et al., 2013), glacial isostatic adjustment (GIA) (e.g., Bradley et al., 2016), and the gravitational, rotational, and deformational effects of cryosphere mass changes (e.g., Mitrovica et al., 2009). Understanding regional variability is critical both to interpreting records of past and modern changes and to generating local projections for effective coastal risk management (Slangen et al., 2016). Long tide-gauge records (i.e., >50 yrs) are required to understand regional variability (Douglas, 2001), but in most tropical latitudes tide-gauge records only began in the latter half of the 20th century (Church & White, 2011). As a result, there is considerable uncertainty in the regional RSL projections in tropical regions. For example, in Singapore (Figure 1), the Tanjong Pagar tide gauge began recording RSL in 1989 (Tkalich et al., 2013). The probabilistic RSL

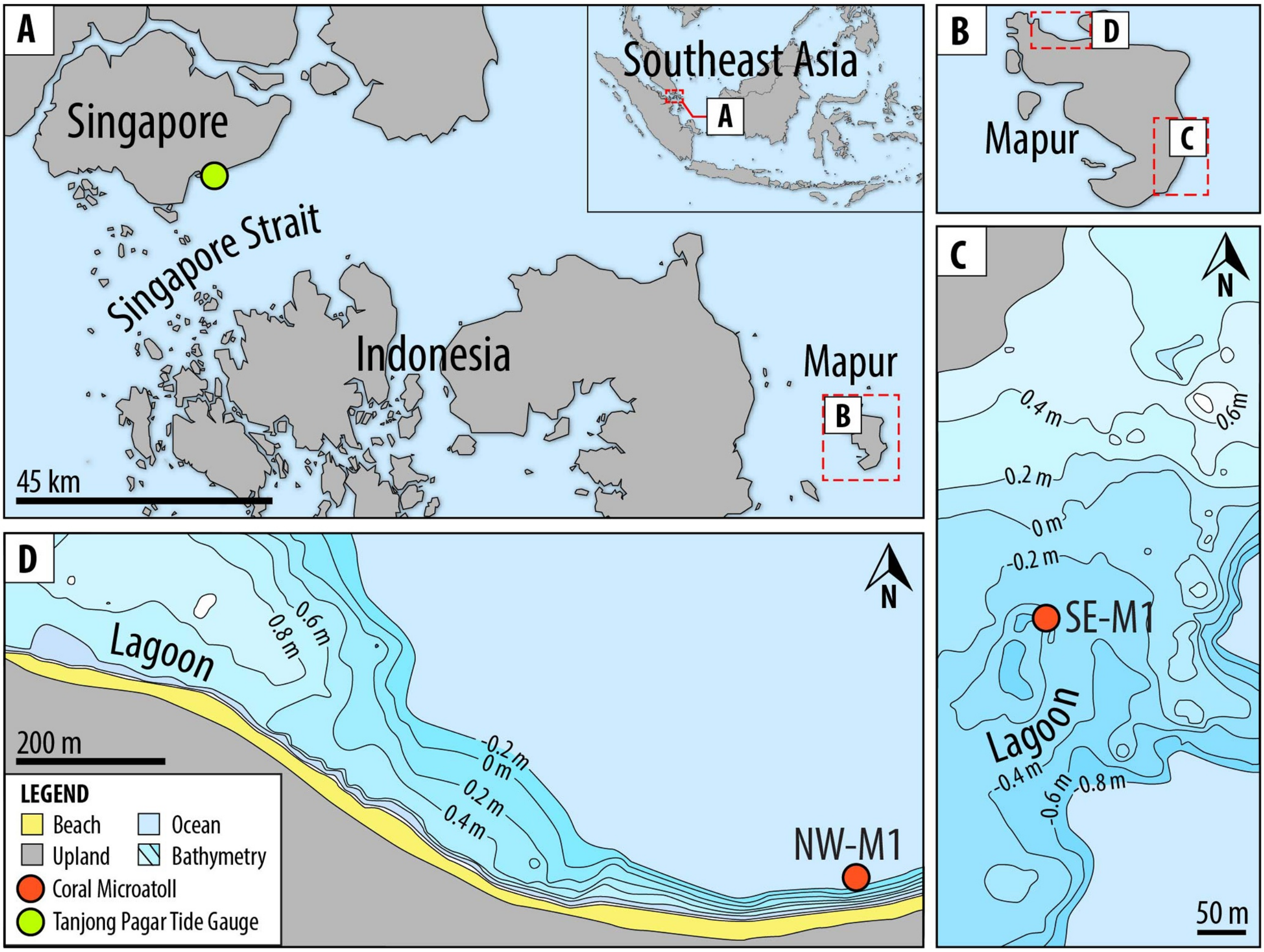

Figure 1. (a) Regional map showing Mapur Island and Singapore. (b) Mapur Island. (c) Southeastern coast of Mapur Island with coral microatoll SE-M1. (d) Northwestern coast of Mapur Island with coral microatoll NW-M1. Bathymetry in (panel c) and (panel d) is relative to highest level of growth measured on open water coral microatolls in 2013, with isobaths drawn every 0.2 m. Isobaths deeper than −0.8 m in (panel c) and −0.2 m in (panel d) are not shown because they were too deep to be surveyed by total station.

projection for Representative Concentration Pathway (RCP) 4.5 at Tanjong Pagar tide gauge is 4–50 cm (5th to 95th percentile) for 2050 (Kopp et al., 2017), with background rates estimated from tide-gauge data around the Singapore coastline ranging from -2.4 ± 1.5 mm/yr to 0.0 ± 2.0 mm/yr (2σ) (Kopp et al., 2014), suggesting that up to ~6 mm/yr of uncertainty could be reduced by using records longer than those provided by local tide gauges (Horton et al., 2018).

The limited number and duration of tide-gauge records in tropical regions can be extended using coral microatolls. Coral microatolls are coral colonies living in the intertidal zone, which are vertically constrained by extreme low water levels (Meltzner & Woodroffe, 2015; Scoffin et al., 1978). A microatoll is identified by concentric ring morphology on its upper surface, which results from short-term fluctuations in the lowest water levels (Figure 2). A microatoll's general morphology reveals important information about RSL during the coral's lifetime (e.g., Meltzner & Woodroffe, 2015): (a) microatolls that rise radially toward their perimeter reflect rising RSL (Figure 2, a1); (b) microatolls with little net change in elevation from the center to the outer ring record RSL stability (Figure 2, a2); and (c) microatolls that fall radially toward their perimeter reflect falling RSL (Figure 2, a3). As RSL rises and falls over time, microatolls record these changes over decades to centuries (Meltzner & Woodroffe, 2015). The vertical uncertainty of the entire coral microatoll record may be on the order of decimeters (Text S1–S2 in the Supporting Information S1; Meltzner et al., 2017). The chronological uncertainty of any portion of a coral microatoll living at the time of sampling can be reconstructed to ~1–2 yrs (Text S3 in the Supporting

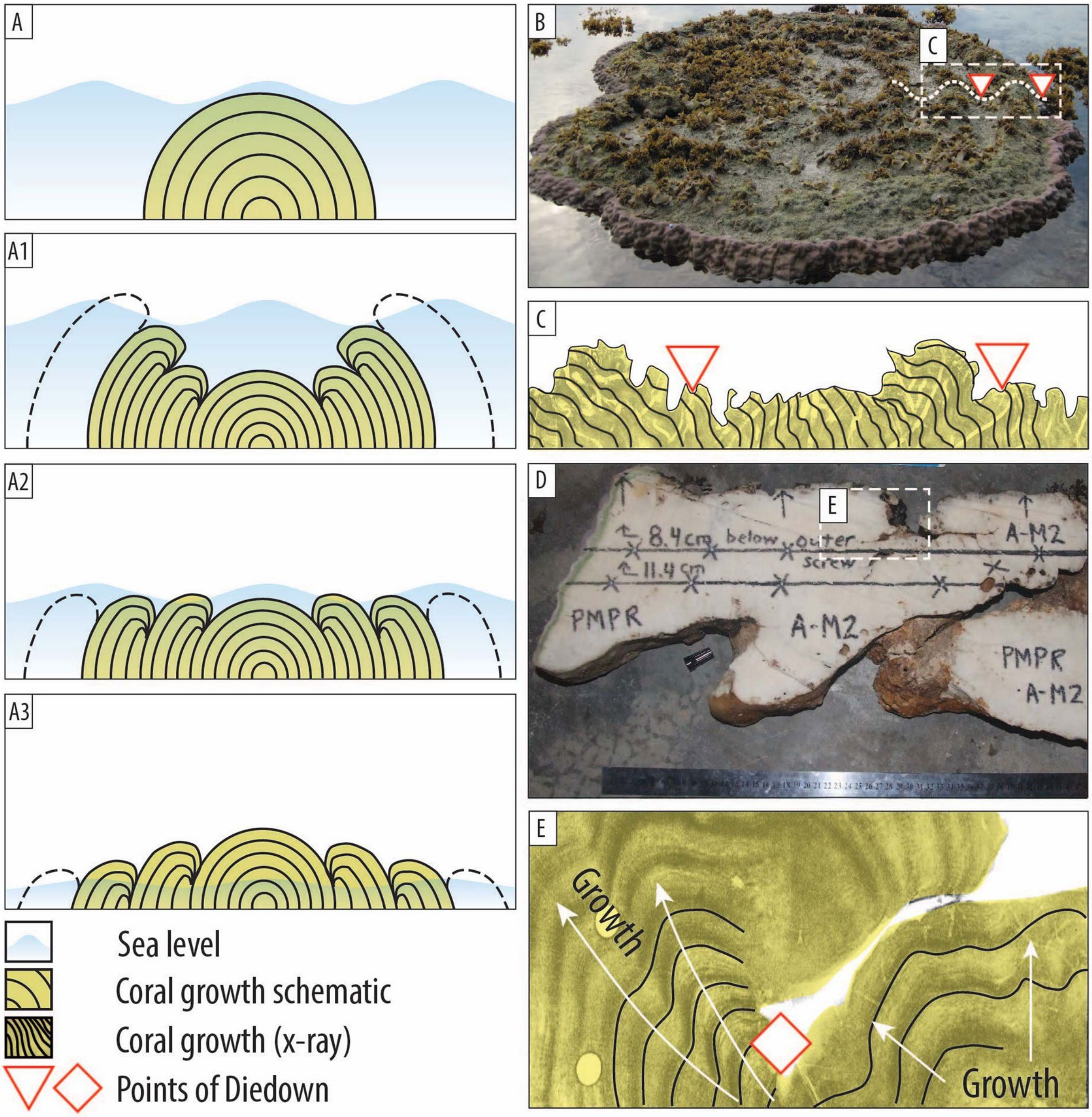

Figure 2. Relative sea-level (RSL) record inferred from a coral microatoll. (a) Schematic of coral microatoll development under conditions of (a1) rising (a2) stable and (a3) falling RSL. (b) Characteristic ring structure on the surface of a *Porites sp*. microatoll. (c) Cross section radiograph of diedowns inferred from surface rings on a coral microatoll (downward-pointing triangles). (d) A microatoll slab cut from a modern coral. (e) Cross section radiograph of a preserved diedown (diamond).

Information S1; Meltzner & Woodroffe, 2015; Smithers & Woodroffe, 2001). The vertical and chronological resolutions of coral microatolls make them a useful proxy for extending tide-gauge records and for providing completely new RSL records.

Here, we examine a RSL record from living coral microatolls from Mapur Island, Indonesia. First, we compare data from the living coral microatolls with the Tanjong Pagar tide gauge in Singapore to validate the proxy technique to reconstruct RSL. Second, we illustrate the improvement of accuracy and precision of 20th and 21st century predictions of RSL change from the combination of the coral microatoll and tide-gauge data.

2. Reconstructing Sea Level Using Coral Microatolls and Tide Gauges

We sampled two *Porites* sp. coral microatolls on Mapur Island, Indonesia, located ~100 km southeast of Singapore (0.99°N, 104.82°E, Figure 1), on the tectonically stable Sundaland (Simons et al., 2007; Wan et al., 2020).

The southeastern coast of Mapur Island has a low elevation coastline with mangroves and fossil coral microatolls, which grew ~0.2–1.2 m above living coral microatolls. Living microatoll SE-M1 was sampled from a deep (>1 m) lagoon that was open to the ocean even at lowest tides (Figure 1c). The northwestern coast of Mapur Island is characterized by a fringing reef formed along an open coastline with sandy beaches and granitic headlands. We sampled microatoll NW-M1 from a freely draining location to open water (Figure 1d). To examine the coral morphology of NW-M1 and SE-M1, we cut 10 cm wide slabs from the center to the outer living edge of each microatoll using a hydraulic chainsaw. The slabs were subsequently recut into ~1 cm slices and radiographed (Meltzner & Woodroffe, 2015).

We reconstructed the elevation of RSL from microatoll diedowns, which are partial mortality events on a coral colony in which the portion of a coral above a certain elevation dies, while coral polyps at lower elevations survive (Meltzner & Woodroffe, 2015) (Text S1 in the Supporting Information S1). We considered diedowns preserved as surface rings (e.g., Figures 2b and 2c) as well as those preserved in structure (Figures 2d and 2e), The highest level of survival (HLS) is the elevation above which all coral polyps died (Taylor et al., 1987). To reconstruct RSL, we convert the HLS data to sea-level index points (SLIP; Shennan & Horton, 2002), by considering four uncertainties in the Mapur data (each reported at 2σ; Text S2 in the Supporting Information S1): (a) variability of the difference between the lowest observed tide (LOT) of the year and the annual mean sea level (MSL) from the Tanjong Pagar tide gauge (±9.5 cm) because coral-microatoll diedowns result from fluctuations of LOT rather than MSL (Meltzner & Woodroffe, 2015); (b) uncertainty from surveying the elevation of the coral microatolls with a total station (±2.0 cm); (c) variability in the HLS on a coral microatoll colony (±3.0 cm); and (d) uncertainty associated with erosion of the coral structure. This last uncertainty is unidirectional, in that erosion can only lower the elevation of a coral, and the true elevation of the SLIP would be higher than the measured point. To represent a symmetrical uncertainty associated with erosion that the model can utilize we first raise the elevation by 4.9 cm, then apply a symmetrical uncertainty (±4.4 cm). This last uncertainty was applied only to data points where the diedown was not preserved in the coral cross section because of erosion.

We reconstructed the chronology of the microatolls by counting annual bands from the living edge of the coral, which was sampled in 2013 (Text S3 in the Supporting Information S1). We digitized images of the radiographs to identify annual bands that correspond to calendar years. We ensured that band marking runs orthogonal to the coral growth lines. Where the diedown is preserved in cross section (Figure 2e) the chronological uncertainty of the diedown is ±1 yr (2σ), but in cases where the points of the diedowns are eroded and must be inferred from the surface rings on a coral microatoll (Figure 2c), the chronological uncertainty of the diedown increases up to ±2 or ±3 yrs (2σ).

To validate the use of coral microatolls as sea-level indicators, we compared diedowns of the coral microatolls to the Tanjong Pagar tide gauge. The Tanjong Pagar tide gauge is the only gauge in Singapore with hourly resolution that is necessary for analysis of LOT (Figure 3) The tide gauge is located on the east coast of Singapore, one of the nearest available records for Mapur (~100 km), and has good record quality (1989–2019, 98% completeness: Table S1 in the Supporting Information S1). Analysis of GIA and sea-surface heights (SSH) both show minimal differences (<0.1 mm/yr) of vertical land motion and ocean dynamics (<2 cm) between Singapore and Mapur Island (Text S4 and Figure S4 in the Supporting Information S1). Therefore, the Tanjong Pagar tide gauge was suitable for validating the coral microatoll record.

3. Validation of the Coral Microatoll Sea-Level Record

We compared the coral microatoll and Tanjong Pagar tide gauge records from 1989 to 2013. Coral microatoll NW-M1 recorded one diedown in 2005, for which the Tanjong Pagar tide gauge also showed a low LOT (Figure 3b). Coral microatoll SE-M1 recorded six diedowns (1988, 1994, 2000, 2005, 2008 and 2012), all of them coincident with low annual LOTs recorded by the Tanjong Pagar tide gauge (Figure 3b). The timing of the diedowns between coral microatolls may be asynchronous due to differences in coral growth rates and/or other local conditions that are not well understood. Our research supports several other studies that have also shown consistency between instrumental records and coral microatolls (e.g., Meltzner et al., 2010; Weil-Accardo et al., 2016; Woodroffe & McLean, 1990).

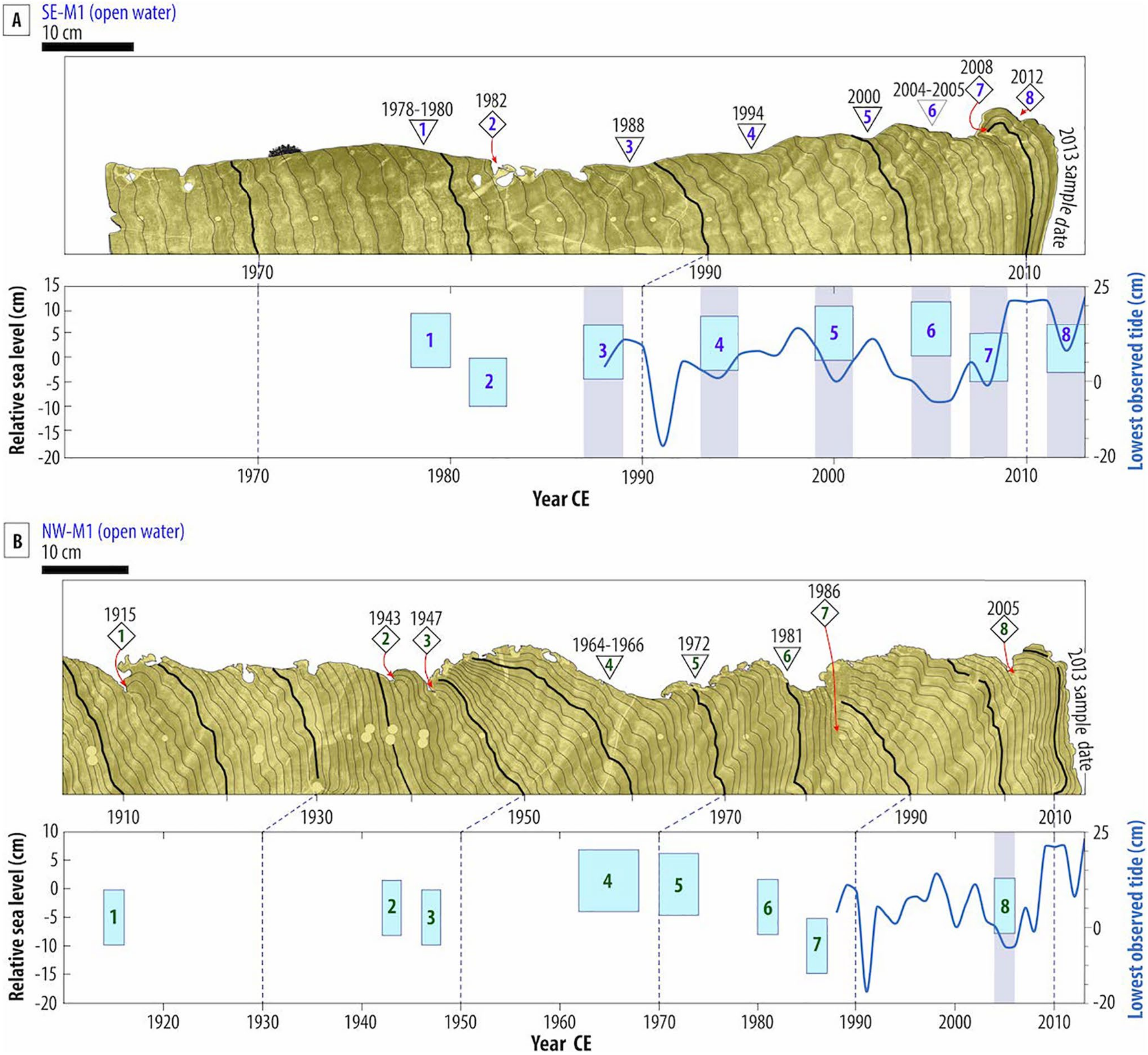

Figure 3. Comparison of coral microatoll sea-level index points (SLIPs) to the lowest observed tide (LOT) of the year from the Tanjong Pagar tide gauge. All records normalized to 2000 CE; vertical uncertainty in coral microatoll SLIPs plotted at 1σ. (a) Open-water record of SE-M1. (b) Open-water record of NW-M1. Triangles mark diedowns deduced from surface rings, diamonds mark diedowns preserved in structure. Note the different *x* and *y* axis scaling between the coral cross sections and their corresponding time series plots. The hourly record for Tanjong Pagar necessary to extract the LOT was obtained from the University of Hawaii Sea Level Center (Caldwell et al., 2015).

The Tanjong Pagar tide gauge recorded the lowest annual LOT (Figure S3 in the Supporting Information S1) in 1991. The lowest annual LOT of 1991 was also recorded in the only nearby tide gauge with hourly records, Sedili tide gauge in Malaysia (Text S5 and Figure S9 in the Supporting Information S1). However, coral microatolls NW-M1 and SE-M1 did not record a diedown (Figure 3). Coral microatoll NW-M1 likely did not have sufficient elevation to respond to the 1991 low water level, as the colony experienced the deepest diedown in its ∼100-year record in 1986 and took until 1993 to recover to its pre-1986 elevation. Such decoupling of coral microatoll records from low water levels for periods of several years has been noted in other studies (e.g., Meltzner et al., 2017; Weil-Accardo et al., 2016). Most of the diedowns of microatoll SE-M1 are recorded in the surface morphology of the colony as troughs between raised rings (Figure S8 in the Supporting Information S1), indicating the SE-M1 microatoll was exposed to more erosion than NW-01 and therefore, erosion was the likely explanation for the lack of a diedown in the surface morphology in 1991 (Meltzner et al., 2017; Smithers & Woodroffe, 2000).

4. Reconstructing 20th Century Rates of Sea-Level Change

To reconstruct RSL we combined coral microatoll data from NW-M1 and SE-M1 with 12 Singapore tide gauges (Figure 4, Figure S5 in the Supporting Information S1). Coral microatoll NW-M1 began to grow before 1882. In the earliest ~30 years of its growth the coral did not preserve diedowns in cross section, but sea-level minimum points indicate sea-level stability within the 2σ uncertainty range of the first SLIP (Figure S1 in the Supporting

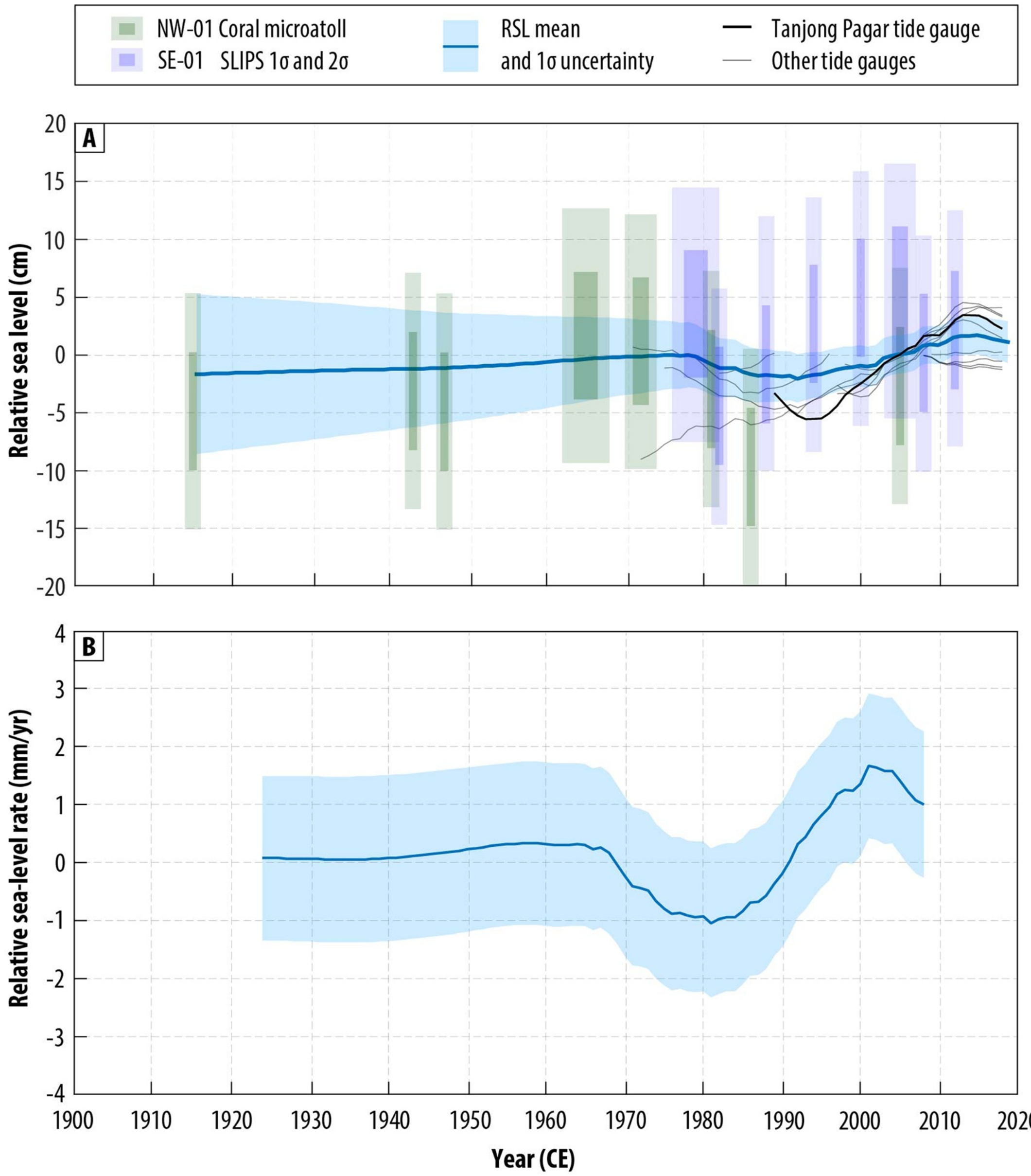

Figure 4. (a) Relative sea-level (RSL) record for Mapur Island, from sea-level index points (SLIPs) of coral microatolls NW-M1 and SE-M1, tide-gauge data for Tanjong Pagar and others in Singapore. Solid line and shaded area represent spatio-temporal model mean and 1σ uncertainty of RSL, respectively. Vertical uncertainty in coral microatoll SLIPs plotted at 1σ and 2σ. (b) Rates of RSL change for Mapur Island based on tide gauges and coral microatolls NW-M1 and SE-M1. RSL rates calculated from 20-year data averages. The hourly record for Tanjong Pagar necessary to extract the LOT was obtained from the University of Hawaii Sea Level Center (Caldwell et al., 2015).

Information S1). The first diedown occurred in 1915, which was followed by seven more with the most recent occurring in 2005 (Figure 3b). The first diedown of coral microatoll SE-M1 occurred around 1978–1980, which was followed by seven more diedowns with the most recent occurring in 2012 (Figure 3a). In total, the two microatolls produced 16 SLIPs with vertical and chronological uncertainties of $\pm$10.2–11.0 cm (2σ) and $\pm$1–3 yrs (2σ), respectively (Table S2 in the Supporting Information S1).

We used a spatio-temporal statistical RSL model (Text S6 and Table S4 in the Supporting Information S1; Ashe et al., 2019; Kopp et al., 2016; Walker et al., 2021) to predict the rates of RSL change at Mapur Island. Comparison of the coral microatoll RSL reconstruction and tide-gauge data agree within their vertical and chronological uncertainties (Figure 4). The combined data of coral microatoll plus tide gauge show RSL was 0.0 $\pm$ 1.6 mm/yr (2σ) from 1915 to 1990 and 1.0 $\pm$ 2.1 mm/yr (2σ) from 1990 to 2019. The inclusion of the coral microatoll data reduced the uncertainty of predictions from the spatio-temporal statistical RSL model by up to 47% (Table S3 in the Supporting Information S1). The remaining uncertainties in the predictions of the combined data reflect the vertical uncertainties in the coral microatoll data and the variability among the 12 Singapore tide gauges, from the influence of land reclamation, coastline modification, as well as RSL variability on the order of weeks to months due to monsoonal wind patterns (Tkalich et al., 2013). The inclusion of the coral microatoll data also improved the probability of identifying a positive RSL trend. A positive trend at Mapur Island is likely (probability $P = 83\%$) over 1990–2019 based on the combination of coral microatoll and tide gauge data, and about as likely as not for 1915–1990 ($P = 49\%$) and 1915–2019 ($P = 64\%$) (Table S3 in the Supporting Information S1). In the absence of microatoll data, a positive trend would be about as likely as not for all three time periods (P between 35% and 63%).

Estimates of GMSL rise for the 20th century range between 1.1 and 1.9 mm/yr (Dangendorf et al., 2019; Frederikse et al., 2020; Hay et al., 2015), higher than the estimate from the combined coral microatoll and tide-gauge data. In Southeast Asia, departures from GMSL may stem from regional processes such as ocean dynamics during monsoons or El Niño-Southern Oscillation/Indian Ocean Dipole events (e.g., Widlansky et al., 2014), vertical land motion from GIA (e.g., Bradley et al., 2016) and/or tectonics (e.g., Majewski et al., 2018). Indeed, GIA models indicate up to 0.5 mm/yr of uplift in the southern Malay Peninsula and Singapore (Figure S4 in the Supporting Information S1).

The sampling bias of a small number of tide gauges in tropical locations with data before 1950 is a major source of uncertainty in understanding GMSL change (Dangendorf et al., 2019; Hay et al., 2015; Holgate et al., 2013). Long instrumental sea-level records (i.e., >50 yrs) are required to understand regional variability, quantify its uncertainty, and decipher its driving processes. However, this lack of long-term tide gauge data can be mitigated through further reconstructions from coral microatolls that are found throughout the tropics including the Indo-Pacific and Caribbean (Meltzner & Woodroffe, 2015; Stoddart & Scoffin, 1979; Weil-Accardo et al., 2016). Coral microatoll sea-level studies, may not only extend RSL records for other regions where tide gauges have only recently been installed but may also act as an independent data source in locations where there are no tide gauges.

Acknowledgments

The research was supported by the National Research Foundation (NRF) Singapore under its NRF Fellowship scheme (Awards NRF-RF2010-04 to ADS and NRF-NRFF11-2019-0008 to AJM), the Singapore Ministry of Education (Awards RGC4/14 to ADS and MOE2019-T3-1-004 to BPH), and the National Research Foundation Singapore and the Singapore Ministry of Education under the Research Centres of Excellence initiative. This research is also supported by the RIE2020 National Sea Level Programme Funding Initiative (Award USS-IF-2020-1), administered by the National Environment Agency, Singapore and supported by the National Research Foundation, Singapore. This paper results from joint-research activities between the Earth Observatory of Singapore–Nanyang Technological University and the Research Center for Geotechnology LIPI. The GIA modelling is conducted in part using the research computing facilities and/or advisory services offered by Information Technology Services, the University of Hong Kong. We express our gratitude to Imam Suprihanto and Dudi Prayudi for assistance in the field and Muhammad Hadi Ikhsan for support with the graphics. We would also like to thank two anonymous reviewers whose comments improved the clarity of the manuscript. This work comprises Earth Observatory of Singapore contribution no. 320. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the NRF, MND and NEA.

Data Availability Statement

Monthly resolution tide gauge data is publicly available at https://www.psmsl.org/data/obtaining/; hourly resolution tide gauge data for Tanjong Pagar tide gauge is publicly available at http://uhslc.soest.hawaii.edu/data/. A summary of tide gauge stations used in the study, sea level index points reconstructed from coral microatoll data, and projected rates of relative sea level are included in the Supporting Information S1 for this paper. Additional data including more photos, survey files and coral microatoll radiograms can be accessed freely at the Nanyang Technological University Data Repository at: https://doi.org/10.21979/N9/USTXO0.

References

Ashe, E. L., Cahill, N., Hay, C., Khan, N. S., Kemp, A., Engelhart, S. E., et al. (2019). Statistical modeling of rates and trends in Holocene relative sea level. *Quaternary Science Reviews*, *204*, 58–77. https://doi.org/10.1016/j.quascirev.2018.10.032

Bradley, S. L., Milne, G. A., Horton, B. P., & Zong, Y. (2016). Modelling sea level data from China and Malay-Thailand to estimate Holocene ice-volume equivalent sea level change. *Quaternary Science Reviews*, *137*, 54–68. https://doi.org/10.1016/j.quascirev.2016.02.002

Caldwell, P., Merrifield, M., & Thompson, P. (2015). Sea level measured by tide gauges from global oceans–The joint Archive for Sea Level holdings (NCEI Accession 0019568), Version 5.5. [Dataset]. NOAA National Centers for Environmental Information, 10, V5V40S47W. https://doi.org/10.7289/V5V40S7W

Church, J. A., & White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, *32*(4–5), 585–602. https://doi.org/10.1007/s10712-011-9119-1

Dangendorf, S., Hay, C., Calafat, F. M., Marcos, M., Piecuch, C. G., Berk, K., & Jensen, J. (2019). Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, *9*(9), 705–710. https://doi.org/10.1038/s41558-019-0531-8

Douglas, B. C. (2001). Sea level change in the era of the recording tide gauge. In *International geophysics* (Vol. 75, pp. 37–64), Academic Press. https://doi.org/10.1016/S0074-6142(01)80006-1

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., et al. (2020). The causes of sea-level rise since 1900. *Nature*, *584*(7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

Hay, C. C., Morrow, E., Kopp, R. E., & Mitrovica, J. X. (2015). Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, *517*(7535), 481–484. https://doi.org/10.1038/nature14093

Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., & Pugh, J. (2013). New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research*, *29*(3), 493–504. https://doi.org/10.2112/JCOASTRES-D-12-00175.1

Horton, B. P., Kopp, R. E., Garner, A. J., Hay, C. C., Khan, N. S., Roy, K., & Shaw, T. A. (2018). Mapping sea-level change in time, space, and probability. *Annual Review of Environment and Resources*, *43*(1), 481–521. https://doi.org/10.1146/annurev-environ-102017-025826

Kemp, A. C., Wright, A. J., Edwards, R. J., Barnett, R. L., Brain, M. J., Kopp, R. E., et al. (2018). Relative sea-level change in Newfoundland, Canada during the past~ 3000 years. *Quaternary Science Reviews*, *201*, 89–110. https://doi.org/10.1016/j.quascirev.2018.10.012

Kopp, R. E., DeConto, R. M., Bader, D. A., Hay, C. C., Horton, R. M., Kulp, S., et al. (2017). Evolving understanding of Antarctic ice-sheet Physics and ambiguity in probabilistic sea-level projections. *Earth's Future*, *5*(12), 1217–1233. https://doi.org/10.1002/2017EF000663

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., et al. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, *2*(8), 383–406. https://doi.org/10.1002/2014EF000239

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., et al. (2016). Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, *113*(11), E1434–E1441. https://doi.org/10.1073/pnas.1517056113

Majewski, J. M., Switzer, A. D., Meltzner, A. J., Parham, P. R., Horton, B. P., Bradley, S. L., et al. (2018). Holocene relative sea-level records from coral microatolls in Western Borneo, South China Sea. *The Holocene*, *28*(9), 1431–1442. https://doi.org/10.1177/0959683618777061

Meltzner, A. J., Sieh, K., Chiang, H.-W., Shen, C.-C., Suwargadi, B. W., Natawidjaja, D. H., et al. (2010). Coral evidence for earthquake recurrence and an A.D. 1390–1455 cluster at the south end of the 2004 Aceh–Andaman rupture. *Journal of Geophysical Research*, *115*, B10402. https://doi.org/10.1029/2010JB007499

Meltzner, A. J., Switzer, A. D., Horton, B. P., Ashe, E., Qiu, Q., Hill, D. F., et al. (2017). Half-metre sea-level fluctuations on centennial timescales from mid-Holocene corals of Southeast Asia. *Nature Communications*, *8*. https://doi.org/10.1038/ncomms14387

Meltzner, A. J., & Woodroffe, C. D. (2015). Coral microatolls. In I. Shennan, A. J. Long, & B. P. Horton (Eds.), *Handbook of sea-level research* (pp. 125–145). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118452547.ch8

Mitrovica, J. X., Gomez, N., & Clark, P. U. (2009). The sea-level fingerprint of West Antarctic collapse. *Science*, *323*(5915), 753. https://doi.org/10.1126/science.1166510

Scoffin, T. P., Stoddart, D. R., & Rosen, B. R. (1978). The nature and significance of microatolls. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *284*(999), 99–122. https://doi.org/10.1098/rstb.1978.0055

Shennan, I., & Horton, B. (2002). Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science*, *17*(5–6), 511–526. https://doi.org/10.1002/jqs.710

Shepherd, A., Irvins, E., Rignot, E., Smith, B., Van den Broeke, M., Velicogna, I., & Scambos, T. (2018). Mass balance of the Antarctic ice sheet from 1992 to 2017. *Nature*, *558*, 219–222. https://doi.org/10.1038/s41586-018-0179-y

Simons, W. J. F., Socquet, A., Vigny, C., Ambrosius, B. A. C., Haji Abu, S., Promthong, C., et al. (2007). A decade of GPS in Southeast Asia: Resolving Sundaland motion and boundaries. *Journal of Geophysical Research*, *112*(B6), 1–20. https://doi.org/10.1029/2005JB003868

Slangen, A. B. A., Adloff, F., Jevrejeva, S., Leclercq, P. W., Marzeion, B., Wada, Y., & Winkelmann, R. (2016). A review of recent updates of sea-level projections at global and regional scales. *Surveys in Geophysics*, *38*(1), 385–406. https://doi.org/10.1007/s10712-016-9374-2

Smithers, S. G., & Woodroffe, C. D. (2000). Microatolls as sea-level indicators on a mid-ocean atoll. *Marine Geology*, *168*(1–4), 61–78. https://doi.org/10.1016/S0025-3227(00)00043-8

Smithers, S. G., & Woodroffe, C. D. (2001). Coral microatolls and 20th century sea level in the eastern Indian Ocean. *Earth and Planetary Science Letters*, *191*(1–2), 173–184. https://doi.org/10.1016/S0012-821X(01)00417-4

Stoddart, D. R., & Scoffin, T. P. (1979). Microatolls: Review of form, origin and terminology. *Atoll Research Bulletin*, *224*. https://doi.org/10.5479/si.00775630.224.1

Taylor, F. W., Frohlich, C., Lecolle, J., & Strecker, M. (1987). Analysis of partially emerged corals and reef terraces in the central Vanuatu Arc. Comparison of contemporary coseismic and nonseismic with quaternary vertical movements. *Journal of Geophysical Research*, *92*(B6), 4905–4933. https://doi.org/10.1029/JB092iB06p04905

Tkalich, P., Vethamony, P., Luu, Q. H., & Babu, M. T. (2013). Sea level trend and variability in the Singapore Strait. *Ocean Science*, *9*, 293–300. https://doi.org/10.5194/os-9-293-2013

Walker, J. S., Kopp, R. E., Shaw, T. A., Cahill, N., Khan, N. S., Barber, D. C., et al. (2021). Common Era sea-level budgets along the U.S. Atlantic coast. *Nature Communications*, *12*, 1–10. https://doi.org/10.1038/s41467-021-22079-2

Wan, J. X. W., Meltzner, A. J., Switzer, A. D., Lin, K., Wang, X., Bradley, S. L., et al. (2020). Relative sea-level stability and the radiocarbon marine reservoir correction at Natuna Island, Indonesia, since 6400 yr BP. *Marine Geology*, *430*, 106342. https://doi.org/10.1016/j.margeo.2020.106342

Weil-Accardo, J., Feuillet, N., Jacques, E., Deschamps, P., Saurel, J. M., Thirumalai, K., et al. (2016). Relative sea-level changes during the last century recorded by coral microatolls in Belloc, Haiti. *Global and Planetary Change*, *139*, 1–14. https://doi.org/10.1016/j.gloplacha.2015.12.019

Widlansky, M. J., Timmermann, A., McGregor, S., Stuecker, M. F., & Cai, W. (2014). An interhemispheric tropical sea level seesaw due to El Niño Taimasa. *Journal of Climate*, *27*(3), 1070–1081. https://doi.org/10.1175/jcli-d-13-00276.1

Woodroffe, C. D., & McLean, R. (1990). Microatolls and recent sea level change on coral atolls. *Nature*, *344*(6266), 531–534. https://doi.org/10.1038/344531a0

References From the Supporting Information

Engelhart, S. E., Horton, B. P., Douglas, B. C., Peltier, W. R., & Tornqvist, T. E. (2009). Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. *Geology*, *37*(12), 1115–1118. https://doi.org/10.1130/G30360A.1

Li, T., Wu, P., Steffen, H., & Wang, H. (2018). In search of laterally heterogeneous viscosity models of glacial isostatic adjustment with the ICE-6G_C global ice history model. *Geophysical Journal International*, *214*(2), 1191–1205. https://doi.org/10.1093/gji/ggy181

Natawidjaja, D. H., Sieh, K., Ward, S. N., Cheng, H., Edwards, R. L., Galetzka, J., & Suwargadi, B. W. (2004). Paleogeodetic records of seismic and aseismic subduction from central Sumatran microatolls, Indonesia. *Journal of Geophysical Research*, *109*(B4). https://doi.org/10.1029/2003JB002398

Peltier, W. R. (1974). The impulse response of a Maxwell Earth. *Reviews of Geophysics*, *12*(4), 649. https://doi.org/10.1029/RG012i004p00649

Peltier, W. R. (2004). Global glacial isostasy and the surface of the Ice-Age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, *32*, 111–149. https://doi.org/10.1146/annurev.earth.32.082503.144359

Peltier, W. R., & Tushingham, A. M. (1989). Global sea level rise and the greenhouse effect: Might they be connected? *Science*, *244*(4906), 806–810. https://doi.org/10.1126/science.244.4906.806

Proshutinsky, A., Ashik, I. M., Dvorkin, E. N., Häkkinen, S., Krishfield, R. A., & Peltier, W. R. (2004). Secular sea level change in the Russian sector of the Arctic Ocean. *Journal of Geophysical Research*, *109*(C3). https://doi.org/10.1029/2003JC002007

Roy, K., & Peltier, W. R. (2017). Space-geodetic and water level gauge constraints on continental uplift and tilting over North America: Regional convergence of the ICE-6G_C (VM5a/VM6) models. *Geophysical Journal International*, *210*(2), 1115–1142. https://doi.org/10.1093/gji/ggx156

Scoffin, T. P., Tudhope, A. W., Brown, B. E., Chansang, H., & Cheeney, R. F. (1992). Patterns and possible environmental controls of skeletogenesis of Porites lutea, South Thailand. *Coral Reefs*, *11*, 1–11. https://doi.org/10.1007/BF00291929

Van de Plassche, O. (1986). *Sea-level research: A manual for the collection and evaluation of data*. Springer.

Whitehouse, P. L. (2018). Glacial isostatic adjustment modelling: Historical perspectives, recent advances, and future directions. *Earth Surface Dynamics*, *6*(2), 401–429. https://doi.org/10.5194/esurf-6-401-2018

Wu, P. (2004). Using commercial finite element packages for the study of earth deformations, sea levels and the state of stress. *Geophysical Journal International*, *158*(2), 401–408. https://doi.org/10.1111/j.1365-246X.2004.02338.x

Zachariasen, J., Sieh, K., Taylor, F. W., & Hantaro, W. S. (2000). Modern vertical deformation above the Sumatran subduction zone: Paleogeodetic insights from coral microatolls. *Bulletin of the Seismological Society of America*, *90*(4), 897–913. https://doi.org/10.1785/0119980016