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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.

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



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

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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

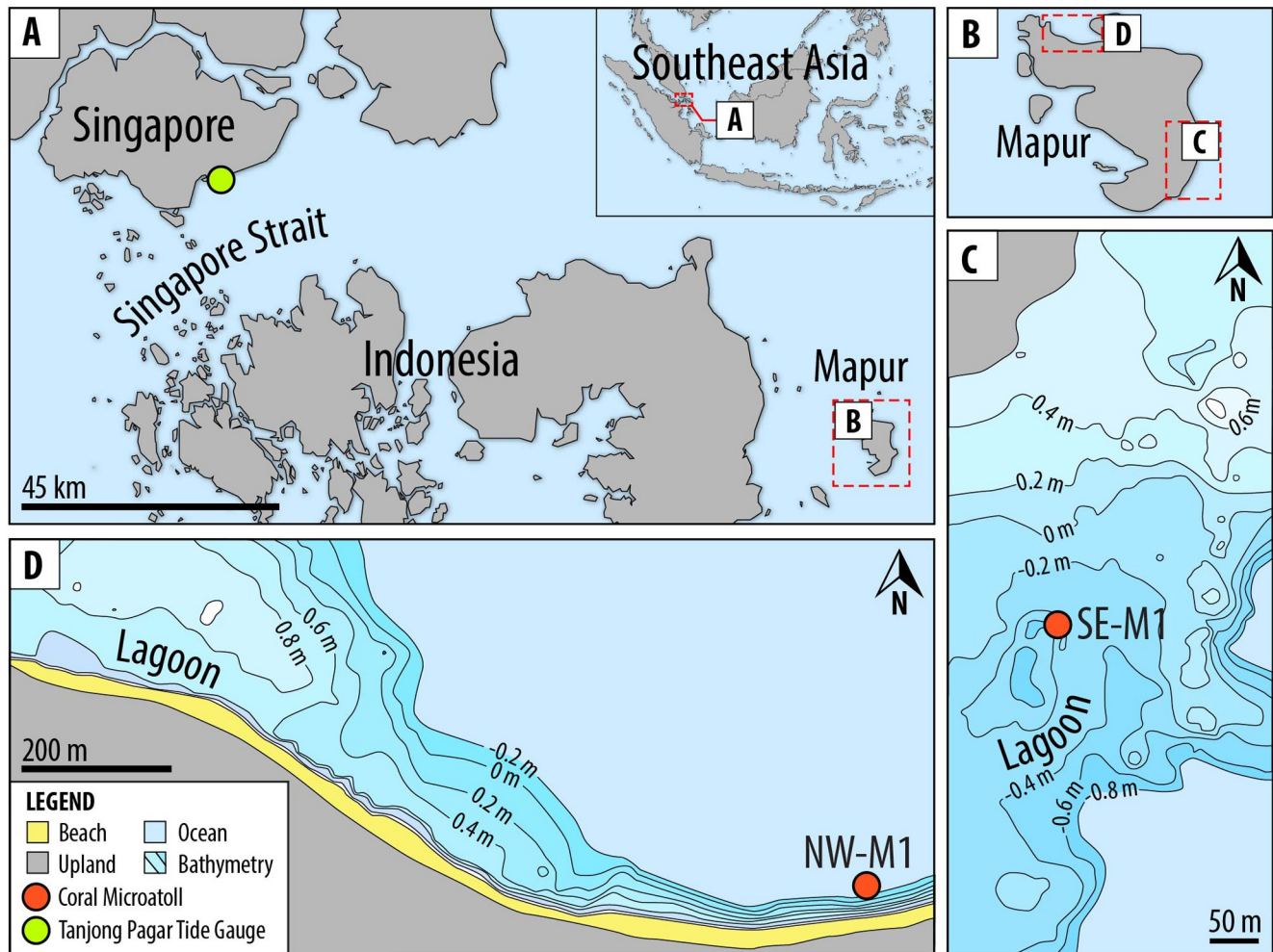


Figure 1. (a) Regional map showing Mapur Island and Singapore. (b) Mapur Island. (c) Southeastern coast of Mapur Island with coral microatoll SE-M1. (d) Northwestern coast of Mapur Island with coral microatoll NW-M1. Bathymetry in (panel c) and (panel d) is relative to highest level of growth measured 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

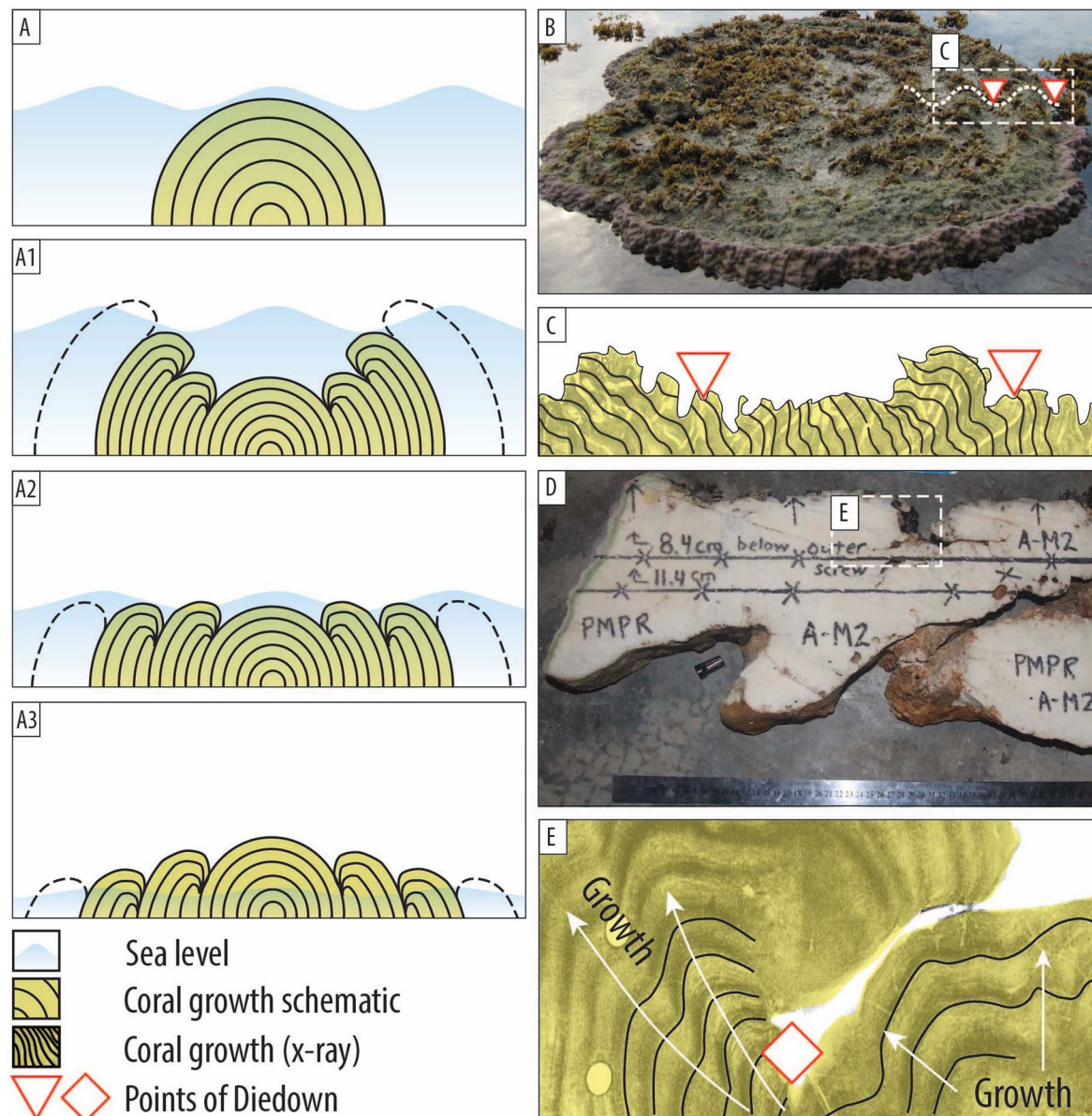


Figure 2. Relative sea-level (RSL) record inferred from a coral microatoll. (a) Schematic of coral microatoll development under conditions of (a1) rising (a2) stable and (a3) falling RSL. (b) Characteristic ring structure on the surface of a *Porites sp.* microatoll. (c) Cross section radiograph of diedowns 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).

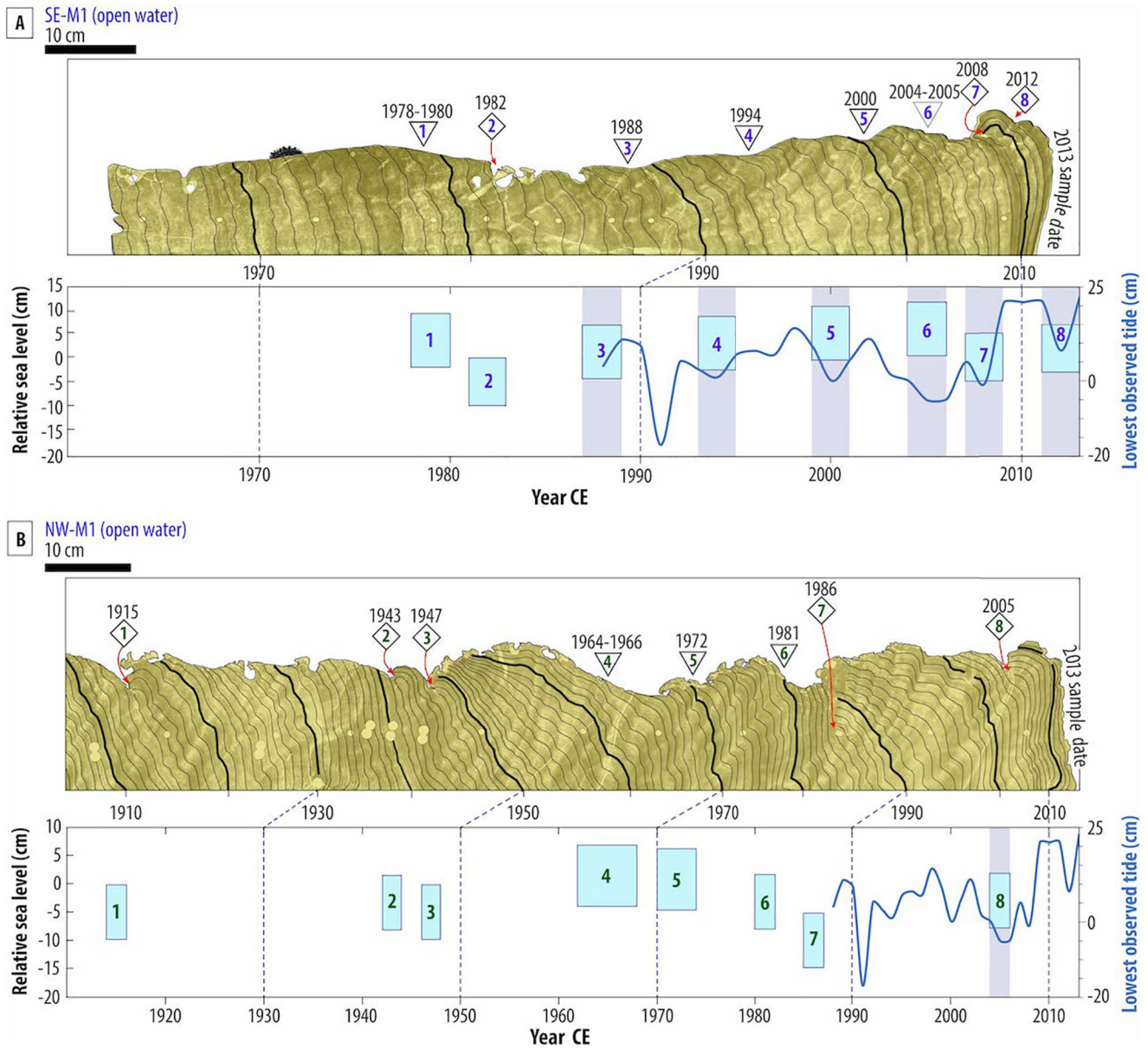


Figure 3. Comparison of coral microatoll sea-level index points (SLIPs) to the lowest observed tide (LOT) of the year from the Tanjung Pagar tide gauge. All records normalized to 2000 CE; vertical uncertainty in coral microatoll SLIPs plotted at 1σ . (a) Open-water record of SE-M1. (b) Open-water record 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 Tanjung Pagar necessary to extract the LOT was obtained from the University of Hawaii Sea Level Center (Caldwell et al., 2015).

The Tanjung 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 2 σ uncertainty range of the first SLIP (Figure S1 in the Supporting

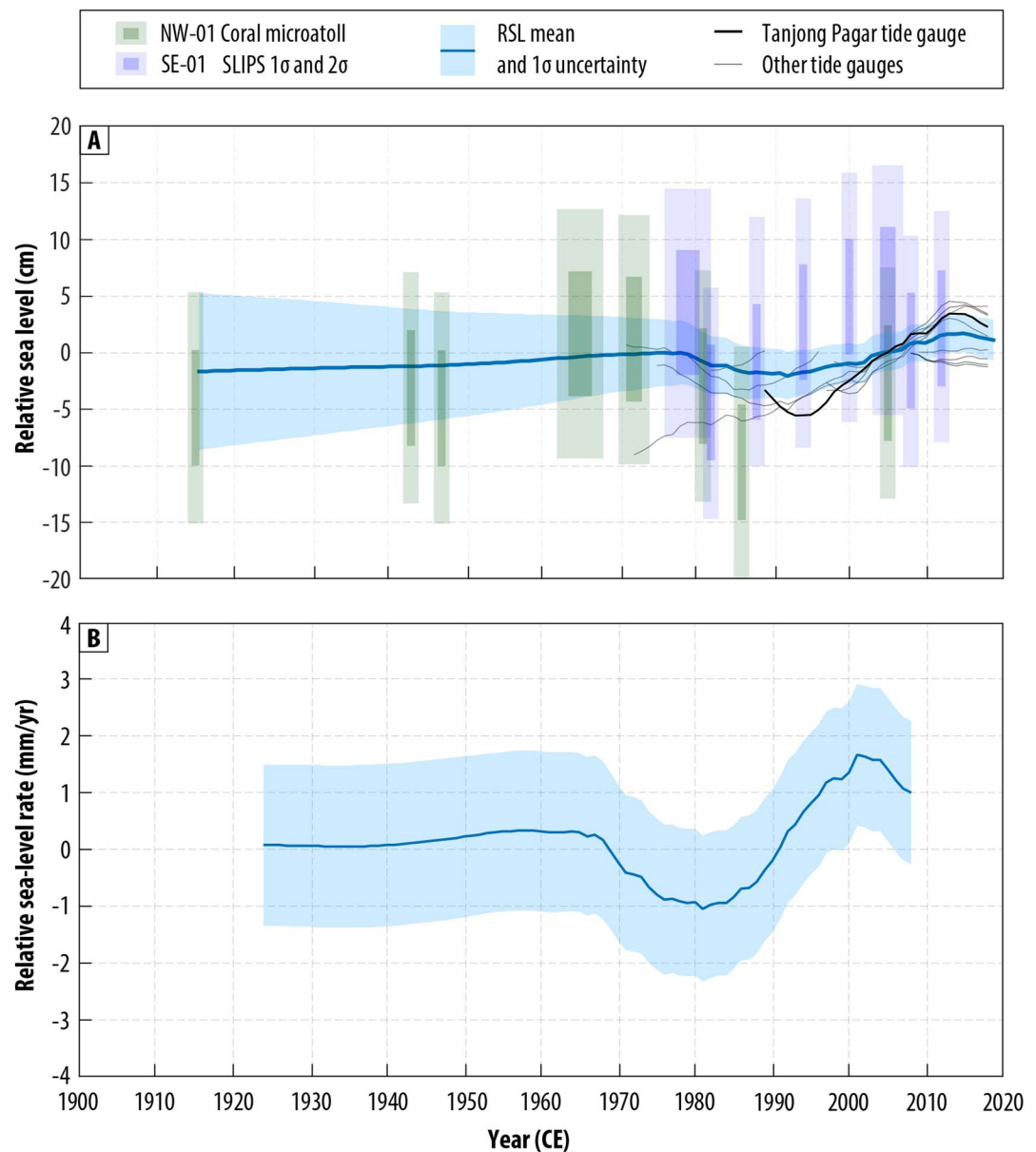


Figure 4. (a) Relative sea-level (RSL) record for Mapur Island, from sea-level index points (SLIPs) of coral microatolls NW-M1 and SE-M1, tide-gauge data for Tanjong Pagar and others in Singapore. Solid line and shaded area represent spatio-temporal model mean and 1 σ uncertainty of RSL, respectively. Vertical uncertainty in coral microatoll SLIPs plotted at 1 σ and 2 σ . (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 ± 10.2 – 11.0 cm (2σ) and ± 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 ± 1.6 mm/yr (2σ) from 1915 to 1990 and 1.0 ± 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; Fredrikse 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.

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/USTX00>.

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