

Reconstructing Late-Holocene relative sea level using mangrove sediments in Singapore

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Abstract

Mangrove sediments have served as valuable archives of Late-Holocene relative sea-level (RSL) change. However, challenges such as age uncertainties due to root penetration and bioturbation, as well as elevation uncertainties from surveying, indicative meaning, and sediment compaction remain. Here, we reconstructed Late-Holocene RSL from Singapore using a multi-proxy approach combining litho- (grain size and loss on ignition), bio- (pollen), and chrono-stratigraphical (Accelerator Mass Spectrometry radiocarbon dating) techniques to produce a series of sea-level index points (SLIPs). We surveyed the SLIPs to mean tide level, quantified the indicative meaning from the contemporary mangrove environment and minimised compaction by producing mostly basal SLIPs. We developed nine SLIPs and assessed RSL change using the Error-In-Variables Integrated Gaussian Process (EIV-IGP) model. We compared the RSL reconstructions with Glacial Isostatic Adjustment (GIA) models and a database of SLIPs from the East Coast of the Malay–Thai Peninsula. Our results show that RSL gradually decreased from 0.33 ± 0.75 m to -0.07 ± 0.17 m between ~4000 cal. yrs. BP and ~500 cal. yrs. BP. The EIV-IGP model suggests RSL *likely* (66% probability) went below present-day levels between ~900 cal. yrs. BP and ~500 cal. yrs. BP, aligning with regional RSL reconstructions but differing from GIA model predictions. Potential drivers of the Late-Holocene RSL fall and subsequent rise to present include global ice-sheet expansion, regional ocean-atmosphere interactions and the subsidence of Sundaland. Future research should refine far-field RSL reconstructions to determine the extent and drivers of Late-Holocene RSL lowstands.

Keywords

rising sea level, Late-Holocene, far-field, Singapore, mangroves, pollen

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Introduction

Rising sea level is an imminent risk to society in a warming world with an estimated 1 billion people being vulnerable to coastal flooding by 2050 (Oppenheimer et al., 2019). The accuracy of sea-level projections relies on the understanding of a variety of global, regional, and local processes that drive relative sea-level (RSL) change (e.g. Kemp et al., 2015; Milne et al., 2009). Ice-equivalent sea-level changes and Glacial Isostatic Adjustment (GIA) control RSL on timescales beyond the instrumental record (e.g. Horton et al., 2018; Yokoyama and Purcell, 2021). Thus, geological proxies are employed to extend the instrumental record of RSL into the Late-Holocene and beyond (e.g. Kemp et al., 2009; Walker et al., 2020).

Late-Holocene RSL from tectonically stable regions that are distant from glaciation centres (far-field regions) are valuable because the GIA signal is minimal and, thus, far-field regions can provide constraints on ice-equivalent sea-level changes (e.g. Lambeck et al., 2014; Whitehouse, 2018). Late-Holocene RSL from far-field regions have been reconstructed from mangrove deposits (e.g. Ellison, 2008; Khan et al., 2022) but there are a variety of complications. Foraminifera and diatoms, which are

commonly used to reconstruct depositional environments, are often poorly preserved due to the degradation of their tests and valves in acidic, high-temperature mangrove environments (e.g. Berkeley et al., 2009; Woodroffe et al., 2005). In contrast, mangrove pollen grains are generally abundant and

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well-preserved in sediments due to their strong exines that can withstand degradation and can be representative of the local vegetation environment (e.g. Ellison, 1996; Engelhart et al., 2007). The reconstruction of Late-Holocene RSL using mangrove sediments is further challenged in two aspects: bioturbation and elevation. Mangrove sediments can often be affected by bioturbation by burrowing organisms or penetration of modern roots into older sediments (e.g. Glaser et al., 2012; Khan et al., 2017; Sefton et al., 2022; Woodroffe et al., 2015). To generate reliable elevation data, compaction of mangrove sediments needs to be considered (e.g. Bird et al., 2004; Toscano et al., 2018) and they must be surveyed to a tidal datum (Shennan and Horton, 2002), which can be challenging in many remote tropical locations.

Late-Holocene RSL has been reconstructed from Singapore and Malaysia using mangrove sediments, which shows sea levels falling below present-day levels from a Mid-Holocene highstand (Bird et al., 2010; Chua et al., 2021; Tam et al., 2018). The Late-Holocene RSL lowstand is not featured in GIA model predictions for the region as existing GIA models do not show evidence of fluctuations in ice-equivalent sea-level during the Late-Holocene (Lambeck et al., 2014, 2017; Li et al., 2023; Peltier et al., 2015). However, the evidence from Singapore is scarce with large data uncertainties (Bird et al., 2010; Chua et al., 2021).

Here, we reconstructed Late-Holocene RSL in Singapore using mangrove sediments from Pulau Ubin, a small offshore island that has not been used for sea-level reconstruction. We employed litho- (grain size and loss on ignition (LOI)), bio- (pollen) and chrono-stratigraphical (Accelerator Mass Spectrometry (AMS) radiocarbon dating) techniques to produce new sea-level index points (SLIPs) that estimate the past position of RSL with corresponding vertical and temporal uncertainties (Engelhart et al., 2011). A series of SLIPs was produced from sediment cores collected from two transects in the terrestrial upland edge of the mangrove zone in Pulau Ubin. Pollen records from sediment cores were produced to characterise the depositional environment. The chronology of the SLIPs was developed using AMS ^{14}C dates on carefully selected plant macrofossils (e.g. plant tissue and wood), bulk sediment and fine-fraction sediment samples to minimise the influence of contamination by modern roots (e.g. Kemp et al., 2013; Sefton et al., 2021). We surveyed contemporary mangrove elevations to determine the indicative meaning of modern mangroves (i.e. their elevational relationship to tidal levels). We compared the SLIPs against the latest iteration of two GIA model predictions (ICE_6G and ANU-ICE). We applied an Error-In-Variables Integrated Gaussian Process (EIV-IGP) model (Cahill et al., 2015) to quantify magnitudes and rates of RSL changes and determine the probability that RSL was below present-day levels during the Late-Holocene.

Study area

Singapore is located at the southern tip of the Malay–Thai Peninsula, Southeast Asia (Figure 1a). Singapore's bedrock geology can be divided into: (1) igneous and metamorphic; and (2) sedimentary rocks. The former consists primarily of widespread batholithic rocks from the Permian and Triassic in the northeastern half of Singapore, with smaller-scale plutonic rocks and an associated aureole of thermally metamorphosed rocks from the Cretaceous outcropping near Pulau Ubin (Gillespie et al., 2019). The latter consists primarily of Triassic to Cretaceous marine to continental sedimentary rocks in the southwestern half of Singapore (Dodd et al., 2019).

Singapore has been inferred to be relatively tectonically stable, experiencing only low strain rates in the central Sunda block (Hall et al., 2004; Simons et al., 2007). The subsidence of the Sunda Shelf at $0.2\text{--}0.3\text{ mm yr}^{-1}$ during the Pleistocene ($\sim 2.58\text{ Ma}$ – 11 ka) is proposed to result from transient dynamic topography, based on analysis of reef morphology and seismic stratigraphy (Sarr et al.,

2019). The Neogene to Quaternary stratigraphy of Singapore consists of a Plio–Pleistocene fluvial unit (Bedok Formation) overlain by Late Pleistocene to Holocene fluvial, littoral and shallow marine deposits (Kallang Group; Bird et al., 2010; Chua et al., 2020, 2021). The Kallang Group can be divided into transgressive and highstand deposits associated with: the Last Interglacial (approximately 125,000–115,000 cal. yrs. BP); a lowstand paleosol that overprints the Last Interglacial deposits; and overlying transgressive and highstand deposits from the Holocene (Chua et al., 2020).

Pulau Ubin is a small island (10.2 km^2) located in northeastern Singapore (Figure 1b). Pulau Ubin has varied relief with low hills composed of primarily granitic, intrusive rocks of Permian to Triassic and Cretaceous age, with infills of littoral, transitional and alluvial sediments from the Quaternary (Gillespie et al., 2019; Waller, 2001). The island contains one of the few remaining pristine mangroves comprising $\sim 15\%$ of Pulau Ubin's total land cover (Gaw et al., 2019; Figure 1c). There are 32 mangrove species found in Pulau Ubin, dominated by *Rhizophora* spp. (Yang et al., 2011). Pulau Ubin is characterised by semi-diurnal tides with a meso-tidal range (mean high water spring to mean low water spring) of $\sim 2.2\text{ m}$ (Marine and Port Authority of Singapore (MPA), 2021). The tides are measured above a fixed chart datum, which is 1.71 m below the Singapore Height Datum (SHD) at the nearest tidal station at Tanjong Changi ($1^\circ 23.4'\text{ N}$, $103^\circ 59.9'\text{ E}$, Figure 1b).

Methods

Field sampling

We established two stratigraphical transects in the terrestrial upland edge of the mangrove zone in the central region of Pulau Ubin to reconstruct Late-Holocene RSL (Figure 1c). Along each transect, we extracted cores at regular elevation intervals using a narrow gouge corer to investigate and describe the sediment stratigraphy. We used a hand-driven Eijkelpamp peat corer (50 cm length $\times$ 5 cm width) to collect cores from selected locations (PUT1C3, PUT1C5, PUT1C6 and PUT2C1, PUT2C2, PUT2C3, PUT2C4, PUT2C5, PUT2C8) along the transects for further laboratory analyses. We followed best practices for sampling by cleaning the corer between successive samples, collecting sediment cores in a cling-wrapped polyvinyl chloride tube and transporting and storing the sediment cores at $<4^\circ\text{C}$ within a few hours (Kemp et al., 2013). We sliced the sediment cores into 2 cm segments for litho-, bio- and chrono-stratigraphical analyses.

The Centre for Geohazard Observations at Nanyang Technological University (NTU) installed elevation benchmarks along the roadside of Jalan Noordin to tie the elevations of the transects to a common datum, Singapore Height Datum (SHD; Figure 1d). We measured the surface elevations of the cores using a Leica Sprinter 250 m digital level and expressed them relative to mean tide level (MTL) using tidal levels predicted from Tanjong Changi tidal station (Supplemental Info 1, Figures 1b and 2).

Lithostratigraphy

Core stratigraphy and colour were described in the field following Troels-Smith (1955) and a Munsell colour chart (Munsell Soil Colour Charts, 2012). We analysed the grain size and LOI to further characterise the lithostratigraphy of key stratigraphic units. Grain size analysis was performed on the red-yellow sandy mud unit (Unit 1) and dark grey-brown sandy silt unit (Unit 2) in cores PUT1C3 and PUT1C6. To prepare for grain size analysis, sediment samples were pre-treated with 10% hydrochloric acid (HCl) to remove the carbonates, and subsequently with 15% hydrogen peroxide (H_2O_2) to remove organic matter, following methods of Switzer and Pile (2015). The grain size analysis was performed using a Malvern Mastersizer 3000 machine, analysed using GRADISTAT and reported using

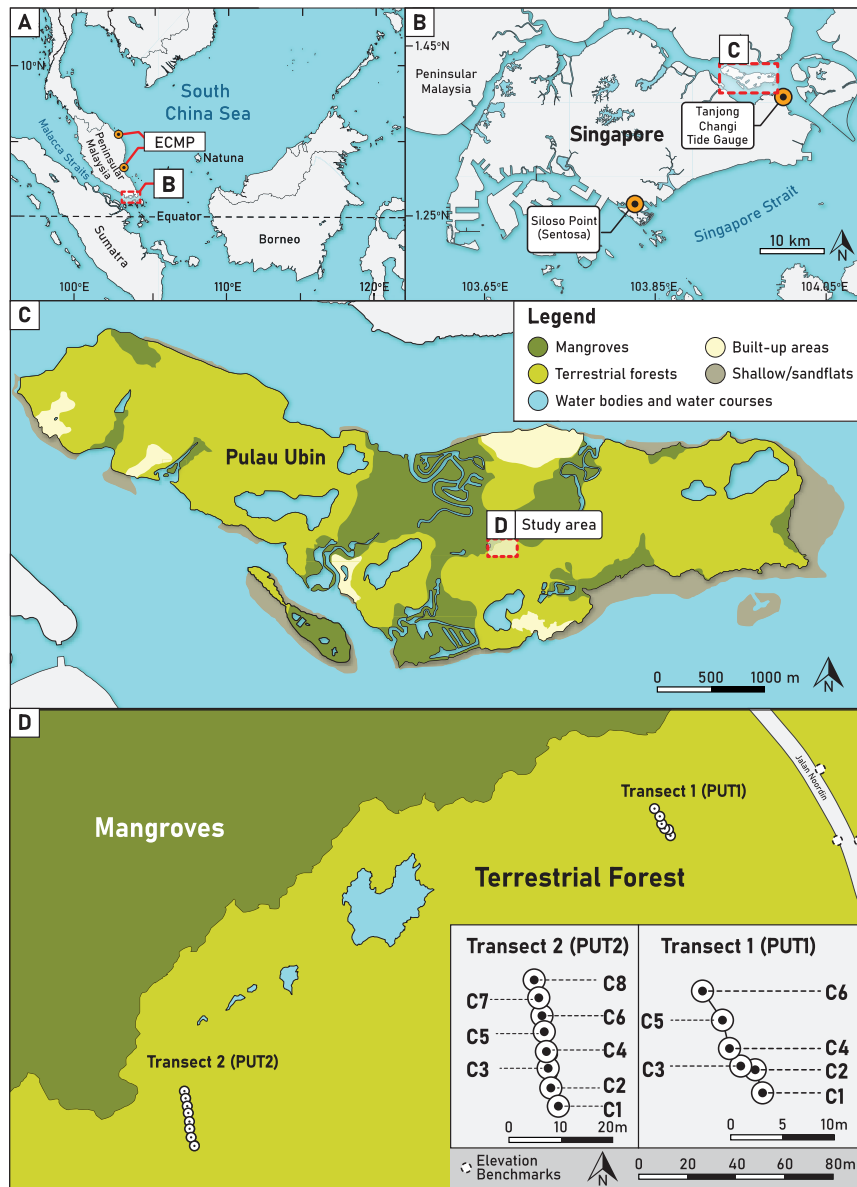


Figure 1. (a) Location of Singapore and East Coast of Malay-Thai Peninsula (ECMP) within Southeast Asia. (b) Location of Pulau Ubin, Tanjong Changi tide gauge and Siloso Point (Sentosa) in Singapore. (c) Map of vegetation zones in Pulau Ubin. (d) Location of cores in transects 1 and 2 (PUT1 and PUT2) in central Pulau Ubin.

Folk's methodology (Blott and Pye, 2001; Folk, 1974; Switzer and Pile, 2015).

We performed LOI to estimate the organic matter content of the sediment cores following methods from Plater et al. (2015). Around 1.25 cm³ of each sample was dried at 105°C overnight to remove moisture, cooled to room temperature in a desiccator and weighed. We calculated the dry bulk density of the sample using the following equation:

$$\text{Dry bulk density} = W / V \quad (1)$$

where W refers to the weight of the sample after being cooled from heating (in grams) and V refers to the volume of the sample (in cm³).

Subsequently, the samples were heated to 550°C for 4 h in a furnace to oxidise organic matter following methods from Heiri et al. (2001). Samples were again cooled to room temperature in a desiccator and weighed following methods from Plater et al. (2015). LOI was calculated using the following formula:

$$\text{LOI} = (W_{105} - W_{550}) / (W_{105}) \times 100\% \quad (2)$$

where W_{105} refers to the dry weight of the sample before heating at 550°C (in grams) and W_{550} refers to the weight of the sample after heating at 550°C (in grams).

Biostratigraphy

We analysed the pollen assemblages in the Units 1 and 2 of PUT1C3 and PUT1C6 to determine the environment of deposition and assess if these stratigraphic units contain mangrove pollen (e.g. Chua et al., 2021; Engelhart et al., 2007). Pollen samples were prepared using a method adapted from Moss (2013) that does not involve hydrofluoric acid. Each sample was dispersed with 10% sodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$) to remove clays, following which one tablet of *Lycopodium* spores was added which serve as markers to determine pollen concentration. Subsequently, the samples were sieved to obtain an 8–125 μm fraction and washed four times. Each wash involved the following steps: add 15 ml distilled water, shake the tube with a vortex mixer, centrifuge and decant the supernatant layer. The sample was then treated with 10% HCl and left overnight to remove carbonates. Next, the pollen was isolated from the sample via the heavy liquid separation method using sodium polytungstate ($\text{Na}_6(\text{H}_2\text{W}_{12}\text{O}_{40})$, density = 1.92–2.00 g/cm³).

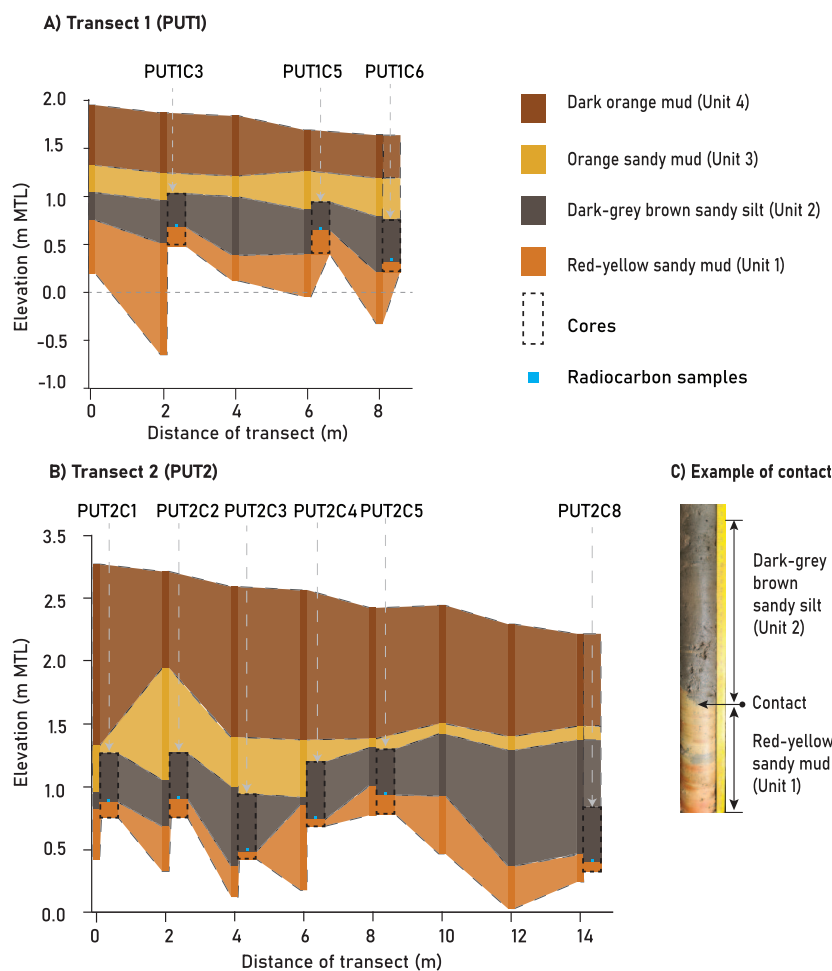


Figure 2. Stratigraphy of sediment cores collected along two transects ((a) PUT1 and (b) PUT2) at the terrestrial upland edge of the mangrove zone of central Pulau Ubin, Singapore and sampled unit 1 and 2 of each sediment core. Dashed lines refer to inferred stratigraphy between thin and Russian cores.

The pollen concentrate was then treated with 10% potassium hydroxide (KOH) to remove humic acids. Acetolysis was not performed to reduce any loss of pollen yield. Lastly, pollen samples were washed to remove KOH before mounting on a microscope slide using glycerol (Moss, 2013).

Lycopodium spores that were added to each sample were used to calculate pollen concentration (grains/g), following the equation:

$$\text{Pollen concentration} = (P_c \times L_a) / (L_c \times G) \quad (3)$$

where P_c is the total number of fossil pollen counted in each sample, L_a is the number of *Lycopodium* spores added in one tablet (14285 ± 501), L_c is the number of *Lycopodium* spores that were counted, and G is the weight of the sample analysed (in grams).

We identified pollen grains and spore morphology with a Leica DM2700M light microscope at $1000\times$ magnification. In each sample, at least 80–100 pollen grains and spores were counted whenever possible. In samples with <80 pollen grains and spores, one entire slide was counted. Pollen grains were classified into mangrove and non-mangrove categories while spores were classified into trilete and monolete spore categories (e.g. Cheng et al., 2020; Mao et al., 2012).

We used the relative abundances of key mangrove pollen taxa such as *Rhizophora*, *Avicennia*, *Bruguiera* and *Sonneratia* to infer ecological zonation (e.g. Nugroho et al., 2024; Yakzan and Hassan, 1997; Yulianto et al., 2005). We interpret a sample to have been deposited in a mangrove environment if the mangrove

taxa constitute greater than 50% of the total assemblage (e.g. Ellison et al., 2017; Rugmai et al., 2023). For example, a seaward fringe mangrove zone is typically dominated by *Rhizophora* pollen, often comprising more than 50% of the total mangrove pollen assemblage (Nugroho et al., 2024). This genus can thrive in saline, frequently inundated environments and be found at the outer edge of mangrove forests (Tomlinson, 2016).

We produced a local pollen and spore identification key to further the application of pollen as a tool to reconstruct paleo-environmental change in Singapore (Supplemental Info 2). The key distinguishes mangrove pollen grains using several features such as the number and position of apertures, complexity of apertures, type of surface sculpturing, size and shape of the pollen grains (e.g. Cheng et al., 2020; Mao et al., 2012). For example, pollen grains from the dominant Rhizophoraceae family commonly have tricolporate apertures, an equatorially elongated endoaperture, psilate to finely reticulate surface sculpturing, size $<20\mu\text{m}$ and subprolate-oblate spheroidal shape (e.g. Cheng et al., 2020; Mao et al., 2012). Another dominant mangrove genus, *Sonneratia*, can be characterised as triplicate, psilate/perforated sculpturing, size $>20\mu\text{m}$ and prolate hexagonal in shape (e.g. Cheng et al., 2020; Mao et al., 2012).

Geochronology

Radiocarbon (^{14}C) dating is a widely used technique to establish the absolute age of samples in Holocene sea-level research (Törnqvist et al., 2015). To minimise contamination by roots, we

extracted macrofossils (wood fragments and plant tissues) and fine-fraction (<63 µm) sediments at specific elevations within sediment cores of Pulau Ubin to produce SLIPs. We also extracted one bulk organic sediment sample, not sieved, for radiocarbon dating and included a bulk uncertainty of ± 100 cal. yrs. (Khan et al., 2019). We do not have paired macrofossil and fine-fraction organic sediment samples at the same sampling depth.

Macrofossils were inspected in distilled water under the microscope and cleaned of fine roots and adhering organic matter following methods of Kemp et al. (2013). Fine-fraction sediment samples were pretreated using acid only and acid-alkali-acid, which provided samples containing both humic acid and humin fractions from the former pretreatment and only the humic acid from the latter treatment (e.g. Sefton et al., 2022; Tan, 2023; Woodroffe et al., 2015). After pretreatment, the fine-fraction samples were washed to neutral with Ultrapure water (Sefton et al., 2022). We have paired fine-fraction sediment samples of different pretreatments at the same sampling depth.

Whenever there were duplicate samples for a particular sampling depth, the ages overlapped except for one sample (Supplemental Info 3). We adopted a conservative approach to consider the maximum and minimum age to derive the age for RSL reconstruction instead of averaging the two ages of each sample. The age derived for RSL reconstruction was the midpoint of the maximum and minimum age of the two dates. The age uncertainty (2σ) of that sampling depth is obtained by subtracting the midpoint value from the minimum age.

All samples were dried in the oven at 50°C in preparation for shipment to Beta Analytic, Miami, Florida, USA for AMS ^{14}C radiocarbon dating following methods of Kemp et al. (2013). Macrofossil samples were pretreated (acid-alkali-acid) by Beta Analytic. The radiocarbon dates were calibrated using the IntCal20 curve (Reimer et al., 2020) using OxCal (Bronk Ramsey, 2009). The age range reported represents the 95th percent credible interval (Bronk Ramsey, 2009).

Reconstructing the indicative meaning of sea-level index points

To produce a SLIP from the mangroves of Pulau Ubin, the indicative meaning must be estimated (Shennan, 1986; van de Plassche, 1986). The indicative meaning of a sea-level indicator refers to its quantifiable elevational relationship to the reference tidal level (Shennan, 1986; van de Plassche, 1986). The indicative meaning is comprised of the indicative range (modern vertical range of the sea-level indicator with reference to a tide level) and the reference water level (central estimate of the indicative range).

To calculate the elevations of the indicative meaning for our samples, we surveyed the upper and lower contemporary mangrove boundaries at Pulau Ubin (e.g. Khan et al., 2022; Sefton, 2020). The upper mangrove border (landward edge) was characterised by mangrove associates (e.g. *Hibiscus tiliaceus*) bordering the terrestrial-mangrove environments. The lower mangrove border (seaward edge) was characterised by major mangrove trees (e.g. *Rhizophora apiculata* and *Avicennia alba*) bordering the intertidal mudflat area. We measured the elevations of the upper and lower mangrove borders using a Leica Sprinter 250m digital level and expressed them relative to MTL. We used the median (50th percentile) elevation of the upper and lower mangrove boundary to calculate the indicative range and reference water level (e.g. Ellison et al., 2022; Khan et al., 2022).

The RSL of each SLIP was calculated using the following equation (Khan et al., 2019; Shennan and Horton, 2002):

$$\text{RSL}_s = E_s - \text{RWL}_s + \text{SC}_s \quad (4)$$

Table 1. Standardised vertical uncertainties used to reconstruct the Singapore sea-level record (adapted from Chua et al., 2021) and an example for Core PUTIC3.

Sources of uncertainty	Description	Example from PUTIC3 (m)
Indicative range	$\pm$ Indicative range/2	± 1.03
Compaction	$\pm$ Compaction/2	± 0.002
Sample thickness	$\pm$ Sample thickness/2	± 0.01
Sampling	± 0.01 m	± 0.01
Core shortening/stretching	± 0.05 m for hand coring	± 0.01
Non-vertical drilling	0.02 m/m depth	0.02
Levelling	± 0.01 m	± 0.01
dGPS	± 0.10 m	± 0.10
Benchmark	± 0.10 m	± 0.10
Total error		± 1.03

where RSL_s refers to the RSL for a given sample (in metres), E_s refers to the elevation of that sample, RWL_s refers to the reference water level and SC_s is the compaction correction for non-basal samples using methods from Bird et al. (2004; Supplemental Info 4), all referenced to MTL.

Vertical uncertainty of sea-level index points

The total vertical uncertainty of each SLIP comprises the indicative range of the sample and several other sources of uncertainty arising from sample collection and processing, including sediment compaction (Hijma et al., 2015).

All SLIPs from Pulau Ubin are collected <5 cm above the basal contact with incompressible paleosol. Basal sediments that overlie an incompressible substrate are more resistant to the effects of sediment compaction (Horton and Shennan, 2009; Törnqvist et al., 2004). We classified samples that were <2 cm above the basal contact as basal sediments within minimal compaction (Love et al., 2016). For sediments collected >2 cm above the basal contact, we applied a compaction uncertainty. The compaction uncertainty was derived from the PUTIC3 core, by applying the Bird et al. (2004) methodology that estimates compaction using grain size distribution and total organic carbon content (Supplemental Info 4).

We calculated the total vertical uncertainty using the following expression (Shennan and Horton, 2002):

$$E_x = (e_1^2 + e_2^2 + \dots + e_n^2)^{0.5} \quad (5)$$

where $e_1, \dots, e_n$ refers to individual sources of error for sample x (Table 1).

We did not include an error for tidal-range change (Hill, 2016; Horton et al., 2013; Khan et al., 2017). We assumed tidal range was stable throughout the Late-Holocene in Singapore. Globally, the greatest paleotidal range changes occurred from the Last Glacial Maximum to the early Holocene (Uehara and Saito, 2019; Wang et al., 2020). Indeed, mid-Holocene paleotides were modelled for the nearby Java Sea and central Sunda Shelf, which showed a change of less than 10 cm compared to present (Meltzner et al., 2017).

Late-Holocene sea-level database for Singapore

We utilised the HOLSEA framework (Khan et al., 2019) to account for the temporal and vertical uncertainties of our SLIPs. We added our SLIPs to the published SLIPs and limiting data of

Bird et al. (2007, 2010), Chua et al. (2021) and Tan et al. (2024) to produce an updated Late-Holocene sea-level database for Singapore (Supplemental Info 5).

To further analyse the Pulau Ubin sea-level data, we adopted the approach of Tan et al. (2024, 2025) to differentiate SLIPs into Grade I and Grade II depending on the following two criteria for SLIPs: (1) usage of microfossil assemblages (e.g. foraminifera, pollen, etc.) to validate the depositional environment (and hence indicative meaning); (2) any plausibility of errors in sample age and elevation (Supplemental Info 5). Grade I included basal or intercalated SLIPs that had compaction uncertainty accounted and SLIPs whose indicative meaning was validated using microfossils. In contrast, Grade II included intercalated SLIPs without a compaction uncertainty and SLIPs whose indicative meaning was not validated using supporting microfossil evidence.

We inputted the sea-level database of Grade I SLIPs into the EIV-IGP model of Cahill et al. (2015) to quantify magnitudes and rates of RSL change during the Late-Holocene. This model considered vertical and temporal uncertainties of the SLIPs and can model non-linear RSL trends. We used the posterior estimates of RSL obtained from the EIV-IGP model to estimate the probability of RSL being below present in the Late-Holocene (i.e. that RSL in a given year t was <0 m). To estimate the probabilities, we let $\theta_x^{(s)}$ be posterior samples of RSL in year x and let p_x be the probability that RSL in year x was <0 m such that

$$p_x = (1/M) \sum_{s=1}^M \mathbb{I}(\theta_x^{(s)} < 0) \quad (6)$$

where $\mathbb{I}$ is an indicator function such that $\mathbb{I}(\text{condition}) = 1$ if the condition in the parentheses holds true and 0 otherwise.

Glacial isostatic adjustment models

The Late-Holocene SLIPs from Pulau Ubin were compared to two GIA models to evaluate the model performance. The two GIA models apply different ice models, ICE-6G_C (Peltier et al., 2015) and ANU-ICE (Lambeck et al., 2014, 2017; Lambeck and Purcell, 2005), but the same 3D Earth model HetML140 (Li and Wu, 2019). The two ice models use different ice-equivalent sea-level histories constrained by different sets of RSL data. Both ice models support the use of a 3D Earth model (Lambeck et al., 2017; Li et al., 2022). The 3D Earth model HetML140 incorporates lateral variations in lithospheric thickness and mantle viscosity (Li et al., 2018; Li and Wu, 2019). We compared each SLIP derived from Pulau Ubin against the GIA model prediction and derived misfit χ -statistics (χ) to quantify the goodness of fit. A smaller misfit χ -statistic implies a better alignment of the model and the data (Li and Wu, 2019).

Results

Lithostratigraphy

We investigated the lithostratigraphy of nine 50 cm sediment cores along two transects from upland of the central region of Pulau Ubin. The lithostratigraphy of the sediment cores from both transects comprises four units (Figure 2). At the base of the cores is a red-yellow (7.5YR/7/8) sandy mud unit (Unit 1). An abrupt contact separates Unit 1 from an overlying dark grey-brown (7.5YR/4/1) sandy silt unit (Unit 2). Unit 2 is overlain by an orange sandy mud (2.5YR/6/8; Unit 3), which is in turn overlain by an upper unit of dark orange mud (5YR/6/8; Unit 4). The contacts between Units 2, 3 and 4 are gradual.

Field descriptions of the lithostratigraphy were supported by the grain size results for Unit 1 and Unit 2 from cores PUT1C3 and PUT1C6 (Figure 3). In PUT1C3, the red-yellow sandy mud unit (Unit 1) comprised $24 \pm 4.3\%$ sand, $56 \pm 10.0\%$ silt, $20 \pm 9.1\%$ clay while the dark grey-brown sandy silt unit (Unit 2) comprised $16 \pm 6.3\%$ sand, $75 \pm 4.0\%$ silt and $9 \pm 2.5\%$ clay. In core PUT1C6, Unit 1 comprised $13 \pm 5.5\%$ sand, $63 \pm 5.0\%$ silt, $24 \pm 10.0\%$ clay while Unit 2 comprised $30 \pm 9.1\%$ sand, $68 \pm 8.8\%$ silt and $2 \pm 0.3\%$ clay.

We additionally conducted LOI and dry bulk density analysis of cores PUT1C3 and PUT1C6. In both cores, Unit 1 and Unit 2 had similar organic matter but different dry bulk densities (Figure 3). In core PUT1C3, we found the organic matter content of Unit 1 and Unit 2 to be $11 \pm 0.2\%$ and $12 \pm 1.0\%$, respectively, while dry bulk density of Units 1 and 2 was $1.4 \pm 0.09 \text{ g/cm}^3$ and $1.1 \pm 0.2 \text{ g/cm}^3$, respectively. In core PUT1C6, we found organic matter content of Unit 1 and Unit 2 to be $11 \pm 0.4\%$ and $10 \pm 0.9\%$, respectively, while dry bulk density of Units 1 and 2 was $1.4 \pm 0.2 \text{ g/cm}^3$ and $1.6 \pm 0.2 \text{ g/cm}^3$, respectively.

Biostratigraphy

We analysed pollen and spores from Unit 1 and Unit 2 from cores PUT1C3 and PUT1C6 (Figure 3). *Lycopodium* spore markers were present in all samples, which suggests that the pollen extraction was successful (e.g. Moss, 2013; Wang et al., 1999). Pollen was absent or in low concentrations ($<10,000$ grains/g) in Unit 1, which suggests that the unit could have been oxidised leading to pollen degradation (Jardine et al., 2015). In cores PUT1C3 and PUT1C6, mangrove pollen (e.g. Rhizophoraceae) was dominant in Unit 2 (mean relative abundance $\sim 70\%$; 10,000 to 100,000 grains/g), suggesting that the sediments were deposited in a mangrove environment (e.g. Ellison et al., 2017; Rugmai et al., 2023; Figure 3). The remaining pollen in Unit 2 comprised non-mangrove plant families such as Euphorbiaceae and Rubiaceae. These families comprise coastal and terrestrial plants with pollen that may be wind and/or water transported into the mangrove environment (Cheng et al., 2020; Dai et al., 2023). Monolete spores were also found in Unit 2.

Geochronology

We produced 12 radiocarbon dates from three plant macrofossils, four pieces of wood, four fine-fraction ($<63 \mu\text{m}$) sediment samples and one bulk organic sediment sample from the dark grey-brown sandy silt unit (Unit 2) of transects 1 and 2 (Table 2). The radiocarbon samples were extracted from PUT1C3, PUT1C5, PUT1C6, PUT2C1, PUT2C2, PUT2C3, PUT2C4, PUT2C5 and PUT2C8. Cores PUT1C6, PUT2C5 and PUT2C8 had two radiocarbon samples while the rest of the cores had one radiocarbon sample. For samples with two radiocarbon dates, the maximum and minimum value of the two sets of radiocarbon dates were used for RSL reconstruction (Table 2). We produced duplicate samples to test the influence of the acid-only and acid-alkali-acid pretreatment.

The calibrated radiocarbon date ranges span the Late-Holocene, from 4133 to 491 cal. yrs. BP. The 2σ errors of the calibrated ages range from 26 to 140 cal. yrs.

Reconstruction of sea-level index points

We measured the elevation of the upper and lower boundaries of the contemporary mangroves at Pulau Ubin to establish the indicative meaning of mangroves. The upper boundary was 1.74 m MTL, and the lower boundary was -0.31 m MTL (Figure 4). Therefore, the reference water level was 0.72 m MTL and the indicative range was ± 1.03 m.

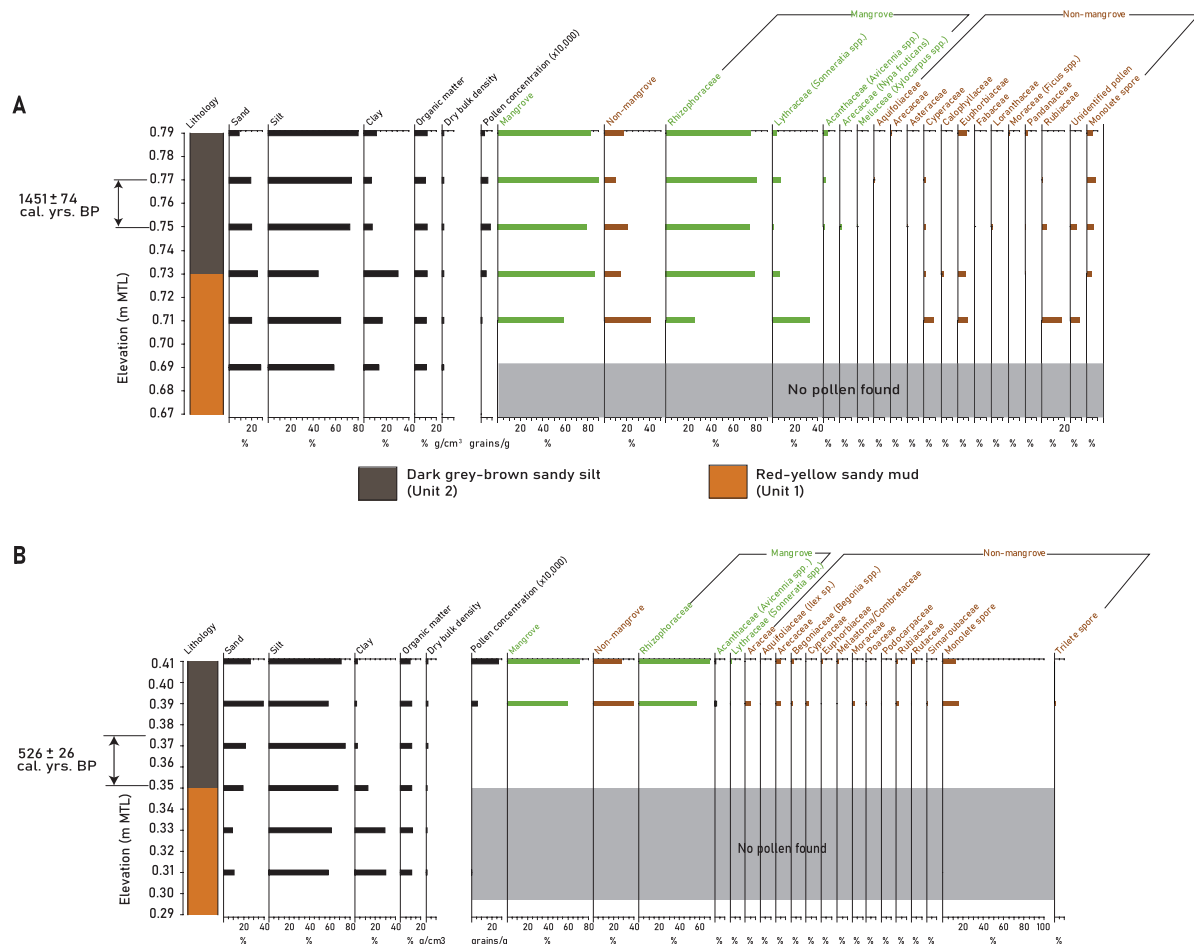


Figure 3. Radiocarbon dates, elevation, stratigraphy, grain size, organic matter content and pollen composition of part of the cores (a) PUTIC3 and (b) PUTIC6. For core PUTIC6, no material was available at elevation -0.36 to -0.38 m MTL. Mangrove pollen were colour coded as green while non-mangrove pollen were colour coded as brown. All remaining variables were in black. The pollen identification key can be found in Supplemental Info 2.

Table 2. AMS ^{14}C radiocarbon ages of samples from Pulau Ubin, Singapore. Radiocarbon ages were calibrated using Intcal20 for the Northern Hemisphere (Reimer et al., 2020) from Oxcal (Bronk Ramsey, 2009).

Sample ID	Material and pretreatment	Laboratory reference number	^{14}C age (CRA)	CRA error	Calibrated age	Calibrated age error (2σ)	$\delta^{13}\text{C}$	Age (cal. yrs. BP)	Age uncertainty (cal. yrs. BP)
PUTIC3 110–111 cm	(Wood): acid/alkali/acid	573813	1560	30	1451	74	-28.0	1451	74
PUTIC5 96–98 cm	(Plant material): acid/alkali/acid	573815	2020	30	1945	102	-28.3	1945	102
PUTIC6 126–127 cm	(Plant material): acid/alkali/acid	573817	500	30	526	26	-28.2	592 ^a	91
PUTIC6 126–127 cm organic sediment	(Bulk organic sediment): acid washes	577615	700	30	623	60	-29.3		
PUT2C1-187	(Plant material): acid/alkali/acid	588808	520	40	565	66	-29.9	565	66
PUT2C2-174.5	(Wood): acid/alkali/acid	588809	2330	30	2322	140	-32.5	2322	140
PUT2C3-206	(Wood): acid/alkali/acid	588810	1440	30	1336	40	-31.5	1336	40
PUT2C4-177	(Wood): acid/alkali/acid	588811	3680	30	4023	110	-27.6	4023	110
PUT2C5-145 fine	(Organic fine fraction sediment): none	597096	670	30	616	57	-29.8	614 ^a	59
PUT2C5-145 fine + acid	(Organic fine fraction sediment): none	597095	650	30	612	57	-30.0		
PUT2C8-177-AAA-BS	(Organic fine fraction sediment): none	603750	530	30	623	60	-30.2	587 ^a	96
PUT2C8-177 acid	(Organic fine fraction sediment): none	603748	470	30	517	25	-30.1		

^aFor these samples, there were two sets of radiocarbon dates. The midpoint of the maximum and minimum of the two datasets were used to represent the mean radiocarbon age for RSL reconstruction.

To illustrate the methodology to reconstruct a SLIP, we provide an example from Core 3 of transect 1 (PUTIC3). The surface elevation of Core 3 was 1.87 m MTL. The PUTIC3 radiocarbon sample was collected at 1.10 m depth from surface at an elevation of 0.77 m MTL. The radiocarbon sample was taken from the base

of Unit 2, 4 cm above the stratigraphical contact between Unit 1 and 2. Compaction of the sample was <0.01 m (Supplemental Info 4). The paleo-depositional environment of the PUTIC3 sample was interpreted as mangrove because the pollen assemblage was dominated by Rhizophoraceae family ($\sim 75\%$; Figure 3). The

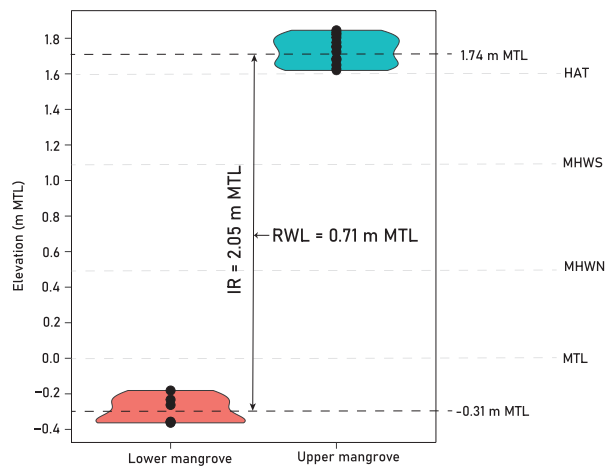


Figure 4. Violin plots of lower mangrove (seaward edge) and upper mangrove (landward edge) border elevations of Pulau Ubin, Singapore. Elevation is estimated with respect to mean tide level (MTL) of Tanjong Changi tidal station (Supplemental Info 1). Dashed lines show the mean lower and upper (50th percentile) mangrove elevations which are used as the indicative range (IR) of mangroves. RWL: reference water level.

reference water level was 0.72 m MTL. The indicative range was ± 1.03 m (Table 1).

The RSL reconstruction for PUT1C3 sample was:

$$RSL_{PUT1C3} = E_{PUT1C3} - RWL_{PUT1C3} + SC_{PUT1C3}$$

$$RSL_{PUT1C3} = 0.77 \text{ m MTL} - 0.72 \text{ m MTL} + 0.002 \text{ m MTL}$$

$$RSL_{PUT1C3} = 0.05 \text{ m}$$

The vertical uncertainty of PUT1C3 was composed of:

$$E_{PUT1C3} = (e_1^2 + e_2^2 + \dots + e_n^2)^{0.5}$$

$$E_{PUT1C3} = (1.03^2_{\text{indicative range uncertainty}} + 0.002^2_{\text{compaction uncertainty}} + 0.01^2_{\text{sample thickness uncertainty}} + 0.01^2_{\text{sampling uncertainty}} + 0.01^2_{\text{core shortening uncertainty}} + 0.02^2_{\text{non-vertical drilling uncertainty}} + 0.01^2_{\text{levelling uncertainty}} + 0.10^2_{(d)GPS \text{ uncertainty}} + 0.10^2_{\text{benchmark uncertainty}})^{0.5}$$

$$E_{PUT1C3} = 1.03 \text{ m}$$

The PUT1C3 sample returned a conventional radiocarbon age (CRA) of 1560 ± 30 ^{14}C yr, which was calibrated to 1450 ± 75 cal. yrs. BP. PUT1C3 was a Grade I SLIP. The PUT1C3 SLIP shows RSL at 0.05 ± 1.03 m at 1450 ± 75 cal. yrs. BP.

A total of nine Grade I SLIPs were produced from radiocarbon dates extracted from Unit 2 across transects 1 and 2 (Figure 5a and Table 3). The SLIPs constrain RSL between 0.06 ± 1.03 m and -0.28 ± 1.03 m from ~ 4000 to ~ 500 cal. yrs. BP (Figure 5a, Supplemental Info 5, Table 3). We added our nine SLIPs to the published Late-Holocene RSL database for Singapore (Chua et al., 2021; Tan et al., 2024). The updated Late-Holocene RSL database consists of 21 Grade I SLIPs, five Grade II SLIPs and four marine limiting data points (Figure 5b).

The EIV-IGP model, applied to Grade I SLIPs, shows a gradual decrease in RSL from 0.33 ± 0.75 m to -0.07 ± 0.17 m between ~ 4000 and ~ 500 cal. yrs. BP, at a rate of $-0.11 \pm 0.06 \text{ mm yr}^{-1}$ (Figure 6a).

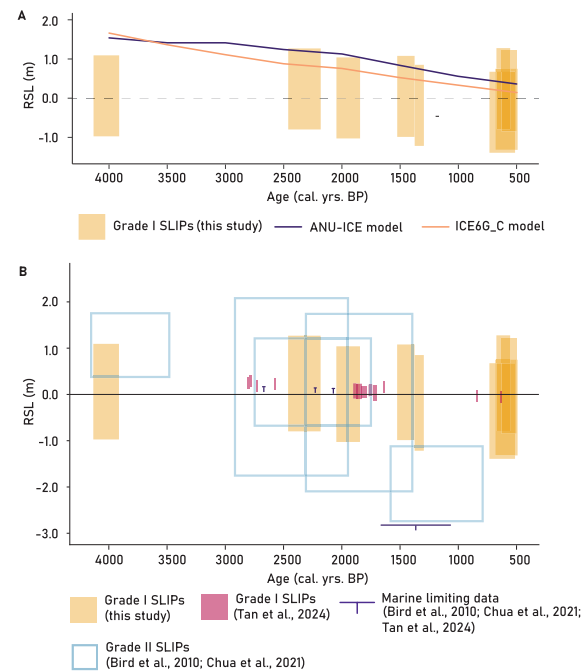


Figure 5. (a) Grade I RSL data from Pulau Ubin, Singapore and comparison to GIA models (ANU-ICE (Lambeck et al., 2014, 2017; Lambeck and Purcell, 2005) and ICE-6G_C (Peltier et al., 2015)). (b) Grade I (Tan et al., 2024; this study) and II (Bird et al., 2010; Chua et al., 2021) RSL data and marine limiting data (Bird et al., 2010; Chua et al., 2021; Tan et al., 2024) from Singapore. Solid fill SLIPs: Grade I SLIPs, Boxed up SLIPs: Grade II SLIPs, T-shaped data points: Marine limiting data. The horizontal line of the marine limiting data points is plotted at the bottom of the RSL uncertainty (2σ) which indicates that RSL could have been at or above the horizontal line. The vertical line of the marine limiting data does not represent the magnitude of RSL uncertainty. RSL: relative sea level; SLIP: sea-level index point.

Table 3. Nine new SLIPs with radiocarbon ages, RSL and their uncertainties reported.

Sample name	RSL (m)	RSL uncertainty (m)	Age (cal. yrs. BP)	Age uncertainty (cal. yrs. BP)
PUT1C3 110–111 cm	0.04	1.03	1451	74
PUT1C5 96–98 cm	0.01	1.03	1945	102
PUT1C6 126–127 cm	-0.36	1.03	592	91
PUT2C1-187–188 cm	0.19	1.03	565	66
PUT2C2-174–175 cm	0.24	1.03	2322	140
PUT2C3-206–207 cm	-0.18	1.03	1336	40
PUT2C4-177–178 cm	0.06	1.03	4023	110
PUT2C5-145–146 cm	0.24	1.03	614	59
fine fraction				
PUT2C8-177–178 cm	-0.28	1.03	587	96
fine fraction				

We estimate the probability of RSL being below present-day levels to be about *as likely as not* (between 33% and 66 % probability) from ~ 1200 to ~ 900 cal. yrs. BP and *likely* (at least 66% probability) from ~ 900 to ~ 500 cal. yrs. BP (Figure 6b).

Discussion

Producing sea-level index points from the mangrove sediments of Singapore

We produced new SLIPs for the Late-Holocene from mangrove sediments of Pulau Ubin, Singapore. For each SLIP, we integrated

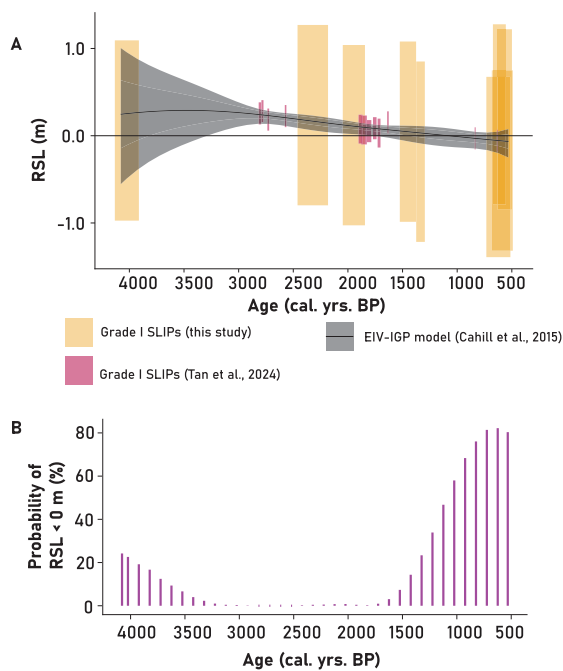


Figure 6. (a) Grade I RSL data from Singapore (Tan et al., 2024; this study) and EIV-IGP model (Cahill et al., 2015) during Late-Holocene. (b) RSL probability < 0 m during Late-Holocene for Singapore. Grey curves indicate 1 σ and 2 σ Error-in-Variables Gaussian Process (EIV-IGP) model RSL results. Solid fill SLIPs: Grade I SLIPs, RSL: relative sea level; SLIP: sea-level index point.

elevational surveys and litho-, bio- and chronostratigraphic data. We accounted for sediment compaction within underlying Holocene sediments whenever necessary.

We used pollen to determine the environment of deposition of the SLIPs. The analysis of sediment cores retrieved from the terrestrial upland edge of the mangrove zone of Pulau Ubin revealed a detailed record of mangrove presence and composition over time to reconstruct paleoenvironments and past RSL changes. Other studies have had success with a pollen-based approach. For example, Zhang et al. (2021) investigated the pollen composition in sediments to produce 15 new mangrove-based SLIPs from the Malay–Thai Peninsula to reconstruct Late-Holocene RSL changes from ~3500 to ~600 cal. yrs. BP. In our mangrove reconstruction, mangrove pollen – particularly *Rhizophoraceae* – was dominant. The consistently high abundance of *Rhizophoraceae* pollen in our assemblages (~70%) supports a localised mangrove occurrence, aligning with observations from other coastal cores where substantial *Rhizophora* spp. representation indicates strong local vegetative influence (e.g. Nugroho et al., 2024; Yakzan and Hassan, 1997; Yulianto et al., 2005). Although *Rhizophora* spp. is partly wind pollinated and has high pollen productivity (Setyaningsih et al., 2019), modern pollen trap studies in Singapore indicate that mangrove pollen has low relative export ability, meaning it is typically deposited close to where the parent plants grow and therefore represents a strong local vegetation signal (Taylor et al., 2001). Pollen, including that of mangroves, is advantageous over other microfossils because sporopollenin (contained within the outer wall of the pollen grain) is resistant to degradation and preserves well in anaerobic sediments (e.g. Bernhardt and Willard, 2015; Engelhart et al., 2007; Urrego et al., 2009). Other microfossils such as foraminifera are known to degrade in acidic mangrove sediments (e.g. Berkeley et al., 2009; Sefton and Woodroffe, 2021; Woodroffe and Horton, 2005).

The new SLIPs were extracted from the basal mangrove sediment unit that lies above a visually consolidated substrate interpreted as a paleosol (Chua et al., 2020). While compaction of

sediments in the paleosol underlying the basal mangrove sediment unit cannot be ruled out due to limitations in core depth, the study site's location at the terrestrial upland edge of the mangrove zone suggests a relatively stable subsurface. In such settings, the substrate typically comprises older, well-consolidated terrestrial deposits (e.g. paleosols), rather than younger, water-saturated marine or estuarine clays that are prone to significant compaction (Brain, 2016; Brain et al., 2012). We assess the base of the mangrove sediment unit as a stable reference subsurface but include a compaction correction term of 0.002 m and vertical uncertainty of ± 0.002 m to account for possible minor compaction within the mangrove sediments themselves (Shennan and Horton, 2002).

To reconstruct RSL, a SLIP must have an indicative meaning (Shennan, 1986; van de Plassche, 1986). The indicative meaning can vary according to the sea-level indicator and is expressed in terms of an indicative range and a reference water level (Shennan, 1986; van de Plassche, 1986). The indicative meaning of mangroves from our study site in Pulau Ubin ranges from 1.74 to –0.31 m MTL, an elevation range of 2.05 m, which is 93% of the meso-tidal range of 2.2 m. Pulau Ubin, Singapore, exhibits a wide elevational range of mangrove elevations as compared to other study sites (e.g. Oh et al., 2017; Syahid et al., 2020; Zhang et al., 2021), potentially due to differences in methodology to calculate the elevational range and local differences in tidal regimes, local hydrogeology and also local disturbances at other study sites such as urbanisation and habitat modification, which may alter sedimentation patterns and tidal dynamics (Balke and Friess, 2016). There are also spatial variations in the indicative meaning of mangroves in Southeast Asia (e.g. Oh et al., 2017; Zhang et al., 2021). For example, in Kuantan, Malaysia, mangrove forests and swamps occupied the elevation range from highest astronomical tides (HAT) to mean high water, which is ~31% of the tidal range (Zhang et al., 2021). The elevation range of mangroves in Pulau Ubin is also larger than the conventional indicative meaning of peat-forming mangroves (HAT to MTL; Khan et al., 2017, 2022; Woodroffe et al., 2016). The mangroves in Pulau Ubin cannot be classified as peat-forming mangroves as sediment organic matter content is below 30% (Plater et al., 2015), which may explain why the indicative meaning of the Pulau Ubin mangroves extends lower in the tidal frame compared to peat-forming mangroves.

It is often challenging to obtain reliable radiocarbon chronologies for SLIPs from mangrove environments due to bioturbation, the lack of plant macrofossils, and penetration of modern roots into deeper sediments (e.g. Kristensen, 2008; Tomlinson, 2016). Bioturbation in mangrove sediments can significantly impact radiocarbon chronologies by disturbing the vertical stratigraphy of sediment layers (Sefton et al., 2021). Organisms such as crabs and worms rework the sediment, mixing older and younger material and potentially introduce younger carbon into deeper layers. This biogenic mixing can blur the temporal resolution of radiocarbon dating, leading to age inversions or anomalously young dates at depth (Sefton et al., 2022). As a result, interpreting sediment cores from mangrove environments requires careful consideration of bioturbation effects to ensure accurate reconstruction of environmental and sea-level histories (e.g. Culver et al., 2015; Punwong et al., 2013).

To reduce the influence of bioturbation, we targeted plant macrofossils. We found seven plant macrofossils of degraded plant tissue and wood. It is noteworthy that wood samples provide maximum radiocarbon ages as they could have been deposited not at the time of death of the plant, but sometime later and can be reworked as they are resistant to degradation (Sefton et al., 2022). The sampled wood material was spongy reddish brown when collected, which we infer to be *Rhizophora* spp. (red mangrove), which is abundant in Pulau Ubin, Singapore (Yang et al., 2011). We also dated four fine-fraction organic sediments (10–63 μ m). Woodroffe et al. (2015) suggests that the 10–63 μ m size fraction

provides a better representation of the age of the mangrove sediments compared to larger sized fractions or bulk sediments. Larger material like roots can be sources of young carbon, and the dating of organic bulk sediments contains a mixture of carbon from diverse sources. For the two paired fine fraction sediment samples of different pretreatments (PUT2C5 and PUT2C8), the sample that contained the humic fraction (PUT2C5-145 fine and PUT2C8-177-AAA-BS) returned similar ages (~4 to ~100 years older) to the sample which contained both humic and humin fractions (PUT2C5-145 fine + acid, PUT2C8-177 acid), suggesting minimal influence from humic acids. However, most previous studies report humic acids yielding younger ages, with some exceptions where they reflect an older carbon source (e.g. Sefton et al., 2022; Tan, 2023). This discrepancy can be explained by humic acids being mobile, which allows younger carbon to be introduced down-core and, conversely, older material to be transported upwards (Sefton et al., 2022).

The resultant ages from the mangrove sediments of Pulau Ubin reduced the temporal uncertainties (26–140 cal. yrs.) compared to the previous Late-Holocene SLIPs of Bird et al. (2010) and Chua et al. (2021; 298–499 cal. yrs.), likely a result from following best practices such as cleaning between successive cores, removal of fine roots and rapid cooling of cores following methods of Kemp et al. (2013).

In this study, the nine new SLIPs were classified as Grade I. Excluding the coral-based SLIPs of Tan et al. (2024), all other SLIPs in the Late-Holocene sea-level database for Singapore were classified as Grade II, because microfossil evidence was not provided to confirm the depositional environment and/or the amount of compaction was not specified (Bird et al., 2007, 2010; Hesp et al., 1998; Tan et al., 2024). Without pollen and other supporting microfossil evidence, there is a possibility that the published SLIPs of Bird et al. (2007, 2010) are not from a mangrove but freshwater depositional environment and therefore could be classified as a terrestrial limiting data point where RSL must be below the data point at a given point in time (Shennan and Horton, 2002).

The vertical uncertainties from this study are reduced (1.03 m) compared to the previous Late-Holocene SLIPs of Bird et al. (2010) and Chua et al. (2021; 1.09–2.00 m), but larger than the vertical uncertainties of $< \pm 0.2$ m (2σ) associated with coral microatoll SLIPs from the Southern Islands of Singapore (Tan et al., 2024). The relatively large errors of the nine new SLIPs are due to the large indicative range of the mangroves, related to the meso-tidal range of ~2.2 m at Pulau Ubin. To reduce the vertical uncertainty in regions of meso- or macro-tidal range, alternative proxies such as coral microatolls (e.g. Tan et al., 2024; Wan et al., 2020) or pollen-based transfer functions (e.g. Engelhart et al., 2007; Lu et al., 2011) could be used. The formation of coral microatolls is driven by subaerial exposure during extreme low tides, and the vertical uncertainty is not strongly influenced by the tidal range. Moreover, Barlow et al. (2013) suggested the vertical error term of transfer-function based reconstructions is typically ~10–15% of the tidal range. For example, the pollen-based transfer function of Engelhart et al. (2007) produced a vertical precision of $< \pm 0.22$ m (2σ) from mangrove sediments in southeast Sulawesi, Indonesia.

Late-Holocene relative sea level in Singapore and other far-field regions

Late-Holocene RSL data from tectonically stable far-field regions provides insights on the timing, magnitude and rates of ice-equivalent sea-level changes and the GIA response (e.g. Deschamps et al., 2012; Horton et al., 2018; Lambeck et al., 2014). The mangrove RSL records from Pulau Ubin show a gradual decrease in RSL ranging from 0.06 ± 1.03 m to -0.28 ± 1.03 m from ~4000 to ~500 cal. yrs. BP. The mangrove RSL records from Pulau Ubin

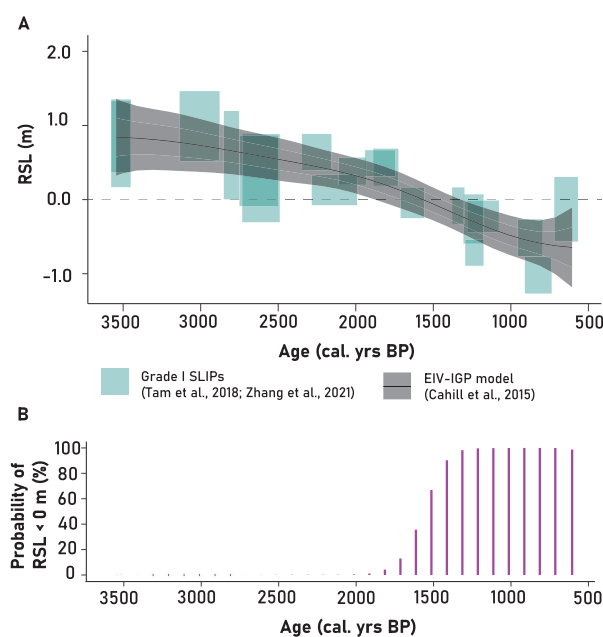


Figure 7. (a) Grade I (Tam et al., 2018; Zhang et al., 2021) RSL data from the East coast of the Malay–Thai Peninsula (ECMP) using the EIV-IGP model (Cahill et al., 2015) for the Late-Holocene. (b) Probability of RSL < 0 m for the ECMP during the Late-Holocene. Grey curves indicate 1σ and 2σ Error-in-Variables Gaussian Process (EIV-IGP) model RSL results. Solid fill SLIPs: Grade I SLIPs, RSL: relative sea level; SLIP: sea-level index point.

align with coral microatoll RSL records from Sentosa, Singapore from ~2500 to ~500 cal. yrs. BP, which showed a slight fall in RSL (Tan et al., 2024). Other records in far-field regions show a larger magnitude of fall in RSL (e.g. Tam et al., 2018; Zhang et al., 2021). For example, RSL reconstructed from mangrove sediments from the east coast of the Malay–Thai Peninsula (ECMP) suggests ~1 m RSL fall from 3500 to ~600 cal. yrs. BP (Zhang et al., 2021; Figure 7a).

We compared the RSL data from Pulau Ubin to two GIA models: ICE-6G_C (Peltier et al., 2015) and ANU-ICE (Lambeck et al., 2014, 2017; Lambeck and Purcell, 2005), which have different ice-equivalent sea-level histories (Figure 5a). The ICE-6G_C model (Peltier et al., 2015) assumes 0 m of ice-equivalent sea-level contribution from the Antarctic ice sheet from 4000 cal. yrs. BP to present, while the ANU-ICE model (Lambeck et al., 2014, 2017; Lambeck and Purcell, 2005) assumes a continuous ice-equivalent sea-level contribution from the Antarctic ice sheet until 2000 cal. yrs. BP. The misfit statistics of the Pulau Ubin SLIPs against the two GIA models are similar: 0.67 and 0.80 for the ICE-6G_C and ANU-ICE models, respectively. Both models predict RSL at the upper end of the SLIP uncertainty boxes between ~2500 and ~500 cal. yrs. BP and overestimate RSL by ~1.5 m for the SLIP at ~4000 cal. yrs. BP. Tan et al. (2024) also observed a similar misfit, suggesting that GIA models with a preference for low upper-mantle viscosities and with refinements to the deglaciation rates of ice sheets would be necessary to achieve a better fit with the Late-Holocene data.

We estimated the magnitude of RSL changes and probability of RSL being below present-day levels in the Late-Holocene using the EIV-IGP model. Previously, Chua et al. (2021) showed RSL below 0 m at ~1000 cal. yrs. BP using Grade II SLIPs. Here, using Grade I SLIPs, we estimate a gradual decrease in RSL from 0.33 ± 0.75 m to -0.07 ± 0.17 m between ~4000 and ~500 cal. yrs. BP, at a rate of 0.11 ± 0.06 mm yr⁻¹. RSL was likely (at least 66% probability) below 0 m between ~900 and ~500 cal. yrs. BP. We applied the EIV-IGP model to Late-Holocene Grade I SLIPs from the neighbouring ECMP (Tam et al.,

2018; Zhang et al., 2021). There was a larger magnitude of RSL fall in the ECMP from 0.84 ± 0.51 m to -0.61 ± 0.60 m between ~3500 and ~600 cal. yrs. BP, with the fall occurring at a rate of 0.47 ± 28 mm yr⁻¹ (Figure 7a). This also revealed that RSL was likely below 0 m from ~1500 to ~600 cal. yrs. BP (Figure 7b; Supplemental Info 5).

There are several local, regional and global processes that can cause RSL to be below present-day levels in the Late-Holocene for Singapore and the Malay–Thai Peninsula. Locally, Sundaland is subsiding at a rate of $0.2\text{--}0.3$ mm yr⁻¹ due to short-lived geodynamic events stimulated by mantle flow (e.g. Hanebuth et al., 2011; Sarr et al., 2019). Assuming a continental subsidence rate of 0.2 mm yr⁻¹ in the last ~500 years, the continental subsidence could account for 0.10 m of RSL rise from ~500 cal. yrs. BP to present-day levels. The subsidence could also account for some of the misfit with the GIA models. Regionally, atmosphere and ocean interactions could also be a contributing factor (Horton et al., 2018). For example, a 0.5 m sea-level variation was recorded by corals between 6850 and 6500 cal. yrs. BP in Belitung Island on the Sunda Shelf (Meltzner et al., 2017). Similar variability in the Late-Holocene could be attributed to interannual and decadal climate variability phenomena such as the El Niño–Southern Oscillation and the Pacific Decadal Oscillation (e.g. Mallinson et al., 2014; Meltzner et al., 2017). Globally, expansion of the Greenland ice sheet from ~2300 to 1200 cal. yrs. BP and rapid RSL rise thereafter during the industrial Common Era (e.g. Kopp et al., 2016; Long et al., 2012) would produce the ice-equivalent sea-level change necessary for the sea-level lowstand.

However, the processes necessary to produce a RSL below present-day levels in the Late-Holocene are debated. In the central Indian Ocean, RSL lowstands of ~−1.4 m at ~1600 cal. yrs. BP were inferred in the Maldives (Kench et al., 2020). Kench et al. (2020) associated the coral microatoll records of RSL lowstands with decreases in radiative forcing and sea surface temperature during the Little Ice Age, but Piecuch et al. (2021) argued the magnitude of the lowstand reported is beyond the limits of climate-driven RSL changes during the Late-Holocene. Short term sea-level variations driven by climate phenomena such as the Little Ice Age can plausibly explain RSL falling below present-day levels but in far-field regions, this is still unresolved (Gehrels, 2010; Kemp et al., 2015). Thus, more data from far-field regions are needed to improve the understanding of the processes driving the below present-day RSL and investigate the presence/absence of a RSL lowstand in the Late-Holocene.

Conclusions

Our reconstruction of Late-Holocene RSL from Pulau Ubin, Singapore, provides new insights into regional sea-level change and enhances the limited dataset available for this far-field tropical setting. By employing litho-, bio- and chrono-stratigraphical techniques, we generated nine new SLIPs that help refine the timing and magnitude of past RSL change.

Our findings show that RSL during the Late-Holocene fell gradually from 0.33 ± 0.75 m to -0.07 ± 0.17 m between ~4000 and ~500 cal. yrs. BP, at a rate of 0.11 ± 0.06 mm yr⁻¹. RSL likely went below present-day levels between ~900 and ~500 cal. yrs. BP. The fall in RSL is consistent with regional reconstructions albeit at a much smaller magnitude in Singapore. There are several global, regional and local processes that can explain the below present-day levels of RSL such as ice-sheet expansion, ocean-atmosphere interactions and subsidence of Sundaland. However, the relative influence of these processes remains debated. Further RSL reconstructions from far-field regions are needed to improve our understanding of the mechanisms driving Late-Holocene RSL variations and potential lowstands.

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Data availability statement

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