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Holocene and Common Era sea level changes in the Makassar Strait, Indonesia

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Abstract

Indonesia is a country composed of several thousand islands, many of them small, low-lying and densely inhabited. These are, in particular, subject to high risk of inundation due to future relative sea level changes. The Spermonde Archipelago, off the coast of Southwest Sulawesi, consists of more than 100 small islands. This study presents a dataset of 24 sea-level index points from fossil microatolls, surveyed on five islands in the Spermonde Archipelago and compares these new results with published data from the same region and with relative sea level predictions from different Glacial Isostatic Adjustment (GIA) models. The newly surveyed fossil microatolls are located around the islands of Tambakulu, Suranti (both ~60 km offshore of Makassar city), Bone Batang and Kodingareng Keke (both located in the center of the Archipelago) and Sanrobengi (located ~20 km south-southwest of Makassar). Results from the near- and mid-shelf islands indicate that relative sea level between 4 to 6 ka BP was less than one meter above present sea level. The only exception to this pattern is the heavily populated island of Barrang Lompo, where we record a significant subsidence when compared to the other islands. These new results support the conclusions from a previous dataset and are relevant to constrain late Holocene ice melting scenarios. Samples from the two outer islands (Tambakulu and Suranti) yielded ages spanning the Common Era that represent, to our knowledge, the first reported for the entire Southeast Asian region.

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

1. Introduction

Sea-level rise is one of the main consequence associated with climate change, and is a major threat for coastal populations all over the globe (IPCC, 2014). In fact, more than half of the human population lives on low-lying islands or along coastlines (Houghton et al, 1996), and it has been estimated that, by 2050, the frequency of coastal flooding may double (Vitousek et al., 2017). Due to the vulnerability of low-lying coastlines and islands to flooding or drowning (Nicholls et al., 1999; Nicholls and Cazenave, 2010) it is essential to understand sea-level variability and its rates at different time scales (Lambeck and Chappell, 2001; Milne et al., 2009).

With the onset of the Holocene (~12 ka BP), after the Last Glacial Maximum, eustatic sea level rose as a result of increasing temperatures and ice loss in polar regions. Locally, sea level departs from the global average due to the combined effects of glacial isostatic adjustment (GIA) (Milne and Mitrovica, 2008), including ocean syphoning (Milne and Mitrovica, 2008; Mitrovica and Milne, 2002; Mitrovica and Peltier, 1991) and the redistribution of water masses due to changes in gravitational attraction and Earth rotation following ice mass loss (Kopp et al., 2015). These processes are superimposed to land level changes due to geological processes, such as subsidence resulting from sediment compaction or tectonics (e.g., Tjia et al. (1972) and Zachariasen, (1998)). Sea-level reconstructions in areas far from polar regions (i.e., far-field, Khan et al., 2015) show a rapid sea-level rise after the onset of Holocene, followed by a GIA-driven sea level highstand in many equatorial areas between 6 and ~3 ka BP (when ice melting was at its maximum), and a subsequent sea-level fall. Thus, far-field locations experienced a higher relative sea level (RSL) in the middle Holocene (e.g. Grossman et al., 1998; Mann et al., 2016) until ice melting rates decelerated.

In most tropical areas, Holocene RSL changes can be reconstructed using several types of RSL indicators (Khan et al., 2015), among which are fossil coral microatolls (e.g. (Scoffin and Stoddart, 1978; Woodroffe et al., 2012; Woodroffe et al. 2014). Microatolls live at Mean Lower Low Water (MLLW), but their living range can span from MLW and LAT. They grow upwards until their polyps reach MLLW, and keep growing horizontally at the same elevation, as soon as they reached this level. If sea level rises above MLW or falls below LAT over extended periods of time, the coral polyps die, retaining their fossil skeleton only. Due to this characteristic, fossil microatolls are often considered as an excellent RSL indicator, when found in good preservation state, as they constrain paleo RSL within MLW to LAT (Meltzner and Woodroffe, 2014). Fossil microatolls can also be easily assigned with an age, either by ^{14}C (Woodroffe et al., 2012) or U-series dating (Azmy et al., 2010). Recent studies also showed that the accurate measurement, dating and standardized interpretation of coral microatolls has the further potential to detail patterns and cyclicities related to short-term Holocene sea level fluctuations (Hallmann et al., 2018; Meltzner et al., 2017).

A recent review of sea level index points in SE Asia, the Maldives, India and Sri Lanka (Mann et al., under rev.) show that, in these regions, microatolls represent ~27% of the 213 sea level index points reported by 31 studies. A study focusing on the Spermonde Archipelago (Mann et al., 2016) reported 20 fossil and 1 modern microatoll on two islands located in the center of the Spermonde Archipelago, SW Sulawesi, Indonesia. In our study, we complement this existing dataset with 24 new fossil microatolls from five additional islands, located up to ~40 km South and ~42 km West from the islands studied by Mann et al. (2016), therefore providing RSL evidence across the entire Spermonde Archipelago.

This study aims to contribute to the current knowledge on late-Holocene relative sea level changes in the Spermonde Archipelago. We focus on newly sampled fossil microatolls (FMA) of five islands in the

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

Archipelago, comparing them with two available datasets from Panambungan, an uninhabited island located 22 km to the northwest of Makassar (Figure 1g) and Barrang Lompo (Figure 1i) (Mann et al., 2016). The latter is densely populated and situated 14 km offshore from Makassar.

2. Regional Setting

Indonesia consists mostly of small and low-lying Islands and coastlines, and includes roughly 15-17.000 islands. The biggest island is Sumatra (~473.000 km²), while the smallest ones are less than 0.2 km² in size. The area of the Spermonde Archipelago, located between 4°00'S to 6°00'S and 119°00' E to 119°30' E, hosts more than one hundred low-lying islands, with averaged elevations of 2 to 3 m above sea level (Janßen et al., 2017; Kench and Mann, 2017). All islands consist of fringing reefs bordering sand and rubble accumulations (Sawall et al., 2011) and some are densely populated (Schwerdtner Máñez et al., 2012). Their low elevation above MSL and the fact that they are composed mostly of calcareous sediments makes them vulnerable to sea level rise, waves and deficits in sediment supply (Kench and Mann, 2017). These reefs bordering these islands are ideal environments for the preservation of microatolls (Mann et al., 2016), but in literature, only a small amount of sea level proxy data was reported to date in the Spermonde Archipelago. Overall, three studies (Tjia et al., 1972; De Klerk, 1982; Mann et al., 2016) report 42 data points, divided into 22 index points, 18 marine limiting (i.e. facies indicating marine conditions) and two terrestrial limiting points (i.e. facies indicating terrestrial conditions). It is worth noting that some of the indicators reported in the Makassar Strait were flagged to be treated with caution in a recent review by Mann et al. (under rev.), mostly as they would indicate mutually inconsistent sea level histories. As an example: Tjia et al. (1972) shows a 6-plus meters sea-level highstand between 4-6 ka BP that Mann et al. (2016) did not confirm based on microatolls of the same age.

The newly surveyed islands, shown in Figure 1, are briefly described hereafter. **Bone Batang** (Figure 1h) is located south of Panambungan and north of Barrang Lompo. This island is a narrow, uninhabited sandbank. South of Barrang Lompo, and 13 km southwest from the city of Makassar, we probed **Kodingareng Keke** (Figure 1c), another uninhabited island. 25 km south of Kodingareng Keke lies the island of **Sanrobengi** (Figure 1d), a small, sparsely inhabited (there are less than 15 houses) reef island located close to the mainland of southern Sulawesi at the coast of Galesong, 21 km south of Makassar city. Sanrobengi is located south of the previous islands, which are close to each other off the coast of Makassar, towards the center of the Archipelago. The fourth and fifth study islands are located northwest of Makassar, bordering the edge of the Spermonde Archipelago. These two outer islands are **Suranti** (Figure 1f) and **Tambakulu** (Figure 1e) and both are uninhabited and located 58 km (Suranti) and 56 km (Tambakulu) from the City of Makassar. Another island already reported and studied by Mann et al. (2016) (Sanane) is included in this study only for the analysis of living microatolls, as fossil microatolls were not found on this island. Its location is 2.7 km northwest of Panambungan, and it is densely populated.

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

Climate of the Past
Discussions
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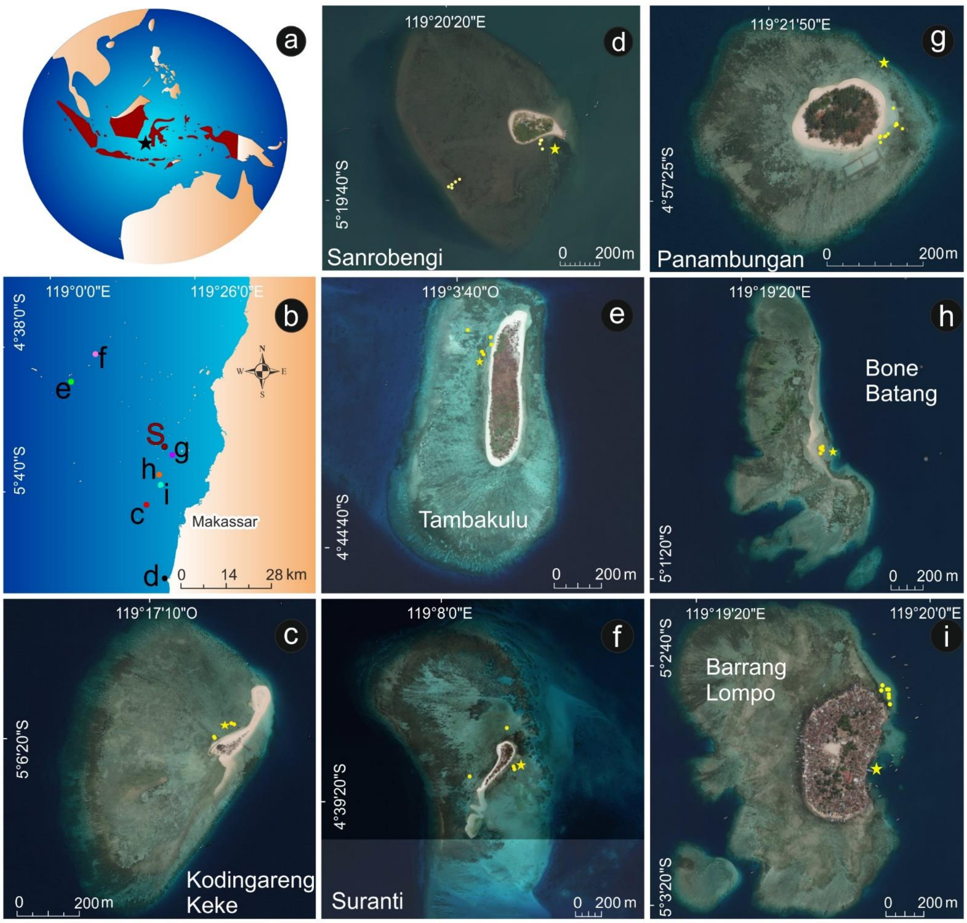

Figure 1. Overview map of the islands investigated by this study and the two islands studied by Mann et al., 2016. The star in a) indicates the location of the Spermonde Archipelago, off the coast of southwestern Sulawesi; b) indicates the position of each island. All letters in b) refer to the aerial views of each island in insets c) to i). The red dot labelled "S" indicates the position of Pulau Sanane, where only living microatolls were surveyed. On insets c) to i), the yellow dots indicate the location of sampled fossil microatolls, while the yellow asterisks indicate the position of the tide pressure sensor. Imagery sources for panels a) and b): Global Self-consistent Hierarchical High-resolution Shorelines from Wessel and Smith (2004) *and for c) to i): Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

3. Methods

Fossil and living microatoll heights on Sanrobengi, Kodingareng Keke, Bone Batang, Suranti and Tambakulu (Figure 1) were surveyed with an automatic level. Their elevations were initially referenced to locally deployed water level sensors acting as temporary benchmarks (stars in Figure 1c-i). These sensors were fixed to either jetties or living corals close to the survey sites and logged the tide levels at 30-seconds intervals. Tidal level differences between the sensors on the study islands were referenced to the tidal height of the water level sensor on Panambungan, for which we have the longest tide record of 8 days and 18 h. The Panambungan tidal readings were compared to readings at the national tide gauge at Makassar harbor to establish the reference of our sample sites to MSL. As a result of annual sea level variability, the mean tidal level at Makassar was slightly above the MSL (+0.035 m), during our surveys. Our local tide gauge readings were corrected accordingly. Despite the Makassar tide gauge is operated since 2011 only (hence providing a relatively short time record), we

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

Climate of the Past
Discussions

compared this time series with our tidal records to estimate MLLW at our study sites. Following this, the long-term consistency and trend of the MSL was tested using radar altimetry data since 1993 (Schöne et al., 2010), where the 19-year MSL trend is around 5mm/a, hence slightly above the global trend.

From our elevation measurements, we calculated paleo RSL applying the concept of indicative meaning (Shennan, 1986) to coral microatolls, using as modern analog living microatolls that were measured in the field. We calculated RSL using the following formula:

$$RSL = E - HLC + Er$$

where **E** is the surveyed elevation of the fossil microatoll; **HLC** is the average height of living coral and **Er** is the estimated portion that was eroded from the upper fossil microatoll surface. The latter value was included in our calculation only in presence of visibly eroded microatolls. The mean thickness of living microatolls in the Spermonde was quantified by Mann et al. (2016) to 0.48±0.19 m. Thus, to reconstruct the original fossil microatoll elevation below MSL, we added the missing centimeters to the actual thickness of eroded fossil microatolls to reconstruct the thickness of 0.48±0.19 m.

Figure 2. Examples of a) non-eroded and b) eroded fossil microatoll at Sanrobengi.

To quantify the error in the RSL calculation, we use the square root of the sum of squares of each single uncertainty term, following the formula:

$$\sigma RSL = \sqrt{\sigma Bm^2 + \sigma E^2 + \sigma HLC^2 + \sigma Er^2}$$

where **σBm** is the individual benchmark error that stems from referencing the local tide and pressure sensor elevation on each island to the tide and pressure sensor elevation of Panambungan. We calculated the elevation difference between the sensor of one island e.g., Sanrobengi and Panambungan (sensor elevation below MSL) to get the sensor elevation below MSL for Sanrobengi and repeated it for each island. Thus, this error is included five times (one per island); **σE** is the elevation error of the survey. Note that, if the automatic level had to be moved due to excessive distance from the benchmark to the measured point, this error is doubled. This had to be done for FMA 1 to 3 in Suranti (tripod was moved twice thus four times this error) and FMA 22 to 26 in Sanrobengi. The **σHLC** is the standard deviation of the height of living coral and **σEr** is the uncertainty in the coral erosion, if the microatoll was eroded.

In order to calculate RSL at each island using a suitable modern analog, we measured HLC at each island or, in case there were no living microatolls found, at the closest neighboring island with living microatolls. We surveyed living microatolls on Tambakulu (n=51) and Sanrobengi (n=24). On Suranti,

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

Kodingareng Keke and Bone Batang, living microatolls were restricted in number and with partly reworked appearance, or completely absent. Therefore, to calculate RSL at this islands, we used HLC elevations from Tambakulu (n=51) for Suranti, from Panambungan (from Mann et al. (2016); n = 20) for Bone Batang, and from Barrang Lompo (from Mann et al. (2016); n=23) for Kodingareng Keke.

Fossil microatolls were sampled by hammer and chisel or with a hand drill. Sub-samples from all samples were analyzed via XRD at the Central Laboratory for Crystallography and Applied Material Sciences (ZEKAM), University of Bremen, Germany, in order to detect possible diagenetic alterations of the aragonite coral skeleton. AMS radiocarbon dating and age calibration to calendar years before present (cal a BP) was done at Beta Analytic Laboratory, Miami, USA. We used the Marine 13 calibration curve (Reimer et al., 2013) and a delta R value of 0±0 as recommended for Indonesia in Southon et al. (2002). In order to compare the new ages to the results from Mann et al. (2016), we recalculated their ages with the same delta R value. We used a different delta R value than Mann et al. (2016) as the value they adopted was measured in a marine reservoir in southern Borneo (Southon et al., 2002) more than 900 km away from our study site (delta R value of 89±70). There is no delta R value available between Sulawesi and southern Borneo that can be used for a radiocarbon age reservoir correction. Due to the long distance between Borneo and our study area and the presence of the Indonesian Throughflow between these two regions (Fieux et al., 1996) there are no bases to assume a similar delta R value between southern Borneo and the Spermonde Archipelago. Therefore we used the delta R value recommended in Southon et al. (2002) that was reported to be derived from unpublished data for the Makassar Strait Indonesia.

We compare the RSL calculated from field data to RSL predicted by geophysical models of Glacial Isostatic Adjustment (GIA), that are based on the solution of the Sea Level Equation (Clark and Farrell, 1976; Spada and Stocchi, 2007). We calculate GIA predictions using a suite of combinations of ice-sheets and solid Earth models (Table 1). The latter are self-gravitating, rotating, radially stratified, deformable and characterized by a Maxwell viscoelastic rheology. We discretize the Earth's mantle in three layers: Upper Mantle, Transition Zone (TZ) and Lower Mantle (LM). Each mantle viscosity profile is combined with a perfectly elastic lithosphere whose thickness ranges from 90 to 120 km (Figure 6). We combine the Earth models with ICE-5G ice-sheet model (Peltier, 2009) and ANICE ice-sheet model (De Boer et al., 2015, 2017) and compute the RSL curves at the sites.

Table 1. Glacial Isostatic Adjustment models used in this study. UM - Upper Mantle (Pas), TZ - Transition Zone (Pas), LM - Lower Mantle (Pas), LT - Lithosphere thickness (km).

Model name	UM	TZ	LM	LT
ICE5G-VM2-90	0.25	0.5	5	90
ICE5G-VM2B-90	0.25	0.25	5	90
ICE5G-VM2-120	0.25	0.5	5	120
ICE5G-VM3-90	0.25	0.5	10	90
ICE5G-VM4-90	0.25	0.5	100	90
ANICE-VM1-100	0.5	0.5	2	100
ANICE-VM2-100	0.5	0.5	5	100
ANICE-VM3-100	0.5	0.5	10	100

4. Results

Our new dataset consists of 17 fossil microatolls with average ages in calendar years ranging from 5956.5±83.5 a BP to 3614.5±98.5 a BP and 8 fossil microatolls with ages varying from 236.5±96.5 a BP to 36.5±11.5 a BP surveyed on five Islands (Table 2). These are added to the 20 fossil microatolls and

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

one modern microatoll from Barrang Lompo and Panambungan previously reported by Mann et al. (2016) (Table 3). During the survey, in comparison to other microatolls on Suranti the microatoll PS_FMA 4 showed evidences of reworking, e.g., its position is plainly deeper than the other fossil microatoll positions on Suranti and it was not securely grounded, thus it was subsequently rejected. Therefore, it is not shown in the results or discussed further.

As shown in Table 2 and Figure 3b, the fossil microatoll of Sanrobengi range in age from 5956.5±83.5 a BP to 3614.5±98.5 a BP, with RSL from 0.14±0.21 m to 0.54±0.28 m. At the same island, the average HLC of 24 living microatolls is -0.36 m with a minimum elevation of -0.48±0.06 m and a maximum of -0.17±0.06 m (Figure 4). Ages of microatolls sampled on the outer islands Tambakulu and Suranti are different from the other islands. On Tambakulu, ages range between 36.5±11.5 a BP and 114±114 a BP. In this time span, the elevations of the fossil microatolls at this island indicate RSL positions between -0.24±0.22 m and 0.11±0.29 m. The living microatoll survey on Tambakulu included 51 individuals showing a maximum elevation of -1.03±0.08 m and a minimum of -0.61±0.08 m. Samples from Suranti show age ranges from 114±114 a BP to 236.5±96.5 a BP. These samples indicate paleo RSL positions of -0.54±0.30 m and -0.12±0.29 m. Fossil microatoll ages from Kodingareng Keke vary from 5868.5±98.5a BP to 5342.5±87.5 a BP, indicating paleo RSL positions between -0.04±0.21 m and 0.08±0.21 m. The samples from Bone Batang cover ages from 5196±118 to 3692.5±107.5 a BP and provide paleo RSL positions of 0.10±0.29 m to 0.17±0.29 m.

Table 2. Fossil microatoll sampled at Sanrobengi (SB_FMA 18 – 26), Tambakulu (PT_FMA 5 – 9), Suranti (PS_FMA 1 – 3), Kodingareng Keke (KK_FMA 14 – 17) and Bone Batang (BB_FMA 11 – 13). All ages are recalculated with the delta R value of 0 ± 0 (Southon et al., 2002).

ID	Island	Mean Age (cal a BP)	Age error	MSL [m]	HLC [m]	RSL [m]	RSL uncertainty [m]
SB_FMA18	Sanrobengi	4954.5	109.5	-0.19	-0.36	0.14	0.21
SB_FMA19	Sanrobengi	5956.5	83.5	-0.11	-0.36	0.22	0.21
SB_FMA20	Sanrobengi	5509.5	66.5	-0.16	-0.36	0.50	0.28
SB_FMA21	Sanrobengi	5970	89	-0.12	-0.36	0.54	0.28
SB_FMA22	Sanrobengi	5550.5	77.5	-0.01	-0.36	0.32	0.22
SB_FMA23	Sanrobengi	4740.5	94.5	-0.01	-0.36	0.32	0.22
SB_FMA24	Sanrobengi	4488.5	91.5	0.00	-0.36	0.48	0.29
SB_FMA25	Sanrobengi	4453.5	92.5	-0.02	-0.36	0.46	0.29
SB_FMA26	Sanrobengi	3614.5	98.5	-0.02	-0.36	0.46	0.29
PT_FMA5	Tambakulu	95	95	-0.89	-0.77	-0.16	0.22
PT_FMA6	Tambakulu	114	114	-0.89	-0.77	-0.16	0.22
PT_FMA7	Tambakulu	112.5	112.5	-0.97	-0.77	-0.24	0.22
PT_FMA8	Tambakulu	36.5	11.5	-0.82	-0.77	0.11	0.29
PT_FMA9	Tambakulu	58	58	-0.95	-0.77	-0.09	0.29
PS_FMA1	Suranti	114	114	-1.47	-0.77	-0.54	0.30
PS_FMA2	Suranti	187.5	91.5	-1.21	-0.77	-0.15	0.29
PS_FMA3	Suranti	236.5	96.5	-1.18	-0.77	-0.12	0.29
KK_FMA14	Kodingareng Keke	5342.5	87.5	-0.46	-0.47	-0.03	0.21
KK_FMA15	Kodingareng Keke	5868.5	98.5	-0.47	-0.47	-0.04	0.21
KK_FMA16	Kodingareng Keke	5519.5	65.5	-0.35	-0.47	0.08	0.21
KK_FMA17	Kodingareng Keke	5519.5	65.5	-0.43	-0.47	0.00	0.21
BB_FMA11	Bone Batang	4869	75	-0.58	-0.50	0.17	0.29
BB_FMA12	Bone Batang	5196	118	-0.65	-0.50	0.12	0.29
BB_FMA13	Bone Batang	3692.5	107.5	-0.67	-0.50	0.10	0.29

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

The recalculated fossil microatoll ages of Barrang Lompo (FMA 1 (BL) to FMA 7 (BL)) range from 4562±136 a BP to 6006.5±112.5 a BP and predict RSL positions between -0.86±0.09 m and -0.44±0.09 m. The modern counterparts (n= 23) show elevations between -0.59±0.05 m and -0.38±0.05 m below MSL, which result in an average HLC of -0.47±0.05 m below MSL (Figure 4). Recalculated ages on Panambungan (FMA 8 (PPB) – FMA 20 (PPB)) vary between 5746.5±109.5 a BP and 3905±100 a BP. FMA 21 (PPB) is modern. RSL predictions for Panambungan range from -0.02±0.11 m to 0.23± 0.11 m. On this study site, a survey of 20 living microatoll provides a minimum elevation of -0.70±0.07 m and a maximum elevation of -0.42±0.07 m below MSL. The average HLC is -0.50±0.07 m below MSL (Figure 4).

Table 3: This table reports the 21 fossil microatolls sampled by Mann et al. (2016) surveyed on Barrang Lompo (FMA 1 (BL) – FMA 7 (BL)) and Panambungan (FMA 8 (PPB) – FMA 21 (PPB). All ages are recalculated with a delta R value of 0 and an error of 0 (Southon et al., 2002).

ID	Island	Mean Age (cal a BP)	Age error	MSL [m]	HLC [m]	RSL [m]	RSL uncertainty [m]
FMA 1 (BL)	Barrang Lompo	4701	108	-1.35	-0.47	-0.86	0.11
FMA 2 (BL)	Barrang Lompo	6006.5	112.5	-0.93	-0.47	-0.44	0.11
FMA 3 (BL)	Barrang Lompo	4562	136	-0.95	-0.47	-0.46	0.11
FMA 4 (BL)	Barrang Lompo	5187	121	-1.03	-0.47	-0.55	0.11
FMA 5 (BL)	Barrang Lompo	5335	99	-1.10	-0.47	-0.62	0.11
FMA 6 (BL)	Barrang Lompo	4878	83	-1.16	-0.47	-0.68	0.11
FMA 7 (BL)	Barrang Lompo	5125	142	-1.07	-0.47	-0.58	0.11
FMA 8 (PPB)	Panambungan	5746.5	109.5	-0.30	-0.50	0.19	0.13
FMA 9 (PPB)	Panambungan	5537.5	78.5	-0.29	-0.50	0.20	0.13
FMA 10 (PPB)	Panambungan	5521	72	-0.27	-0.50	0.22	0.13
FMA 11 (PPB)	Panambungan	5686	101	-0.26	-0.50	0.23	0.13
FMA 12 (PPB)	Panambungan	5193	131	-0.38	-0.50	0.11	0.11
FMA 13 (PPB)	Panambungan	5278	150	-0.29	-0.50	0.20	0.11
FMA 14 (PPB)	Panambungan	3905	100	-0.50	-0.50	-0.02	0.11
FMA 15 (PPB)	Panambungan	4879	75	-0.44	-0.50	0.05	0.11
FMA 16 (PPB)	Panambungan	4479	88	-0.47	-0.50	0.02	0.11
FMA 17 (PPB)	Panambungan	4466.5	103.5	-0.49	-0.50	-0.01	0.11
FMA 18 (PPB)	Panambungan	5106.5	149.5	-0.44	-0.50	0.05	0.11
FMA 19 (PPB)	Panambungan	5279	146	-0.33	-0.50	0.16	0.11
FMA 20 (PPB)	Panambungan	5724	118	-0.34	-0.50	0.15	0.13
FMA 21 (PPB)	Panambungan	modern	modern	-0.44	-0.50	0.04	0.11

Data from Table 1 and Table 2 are plotted in Figure 3. The location of each study site is indicated in Figure 3a) by letters and dots that are representing the colors of the related graphs. Locally measured HLC, used to calculate RSL as reported in the methods, is plotted in Figure 4.

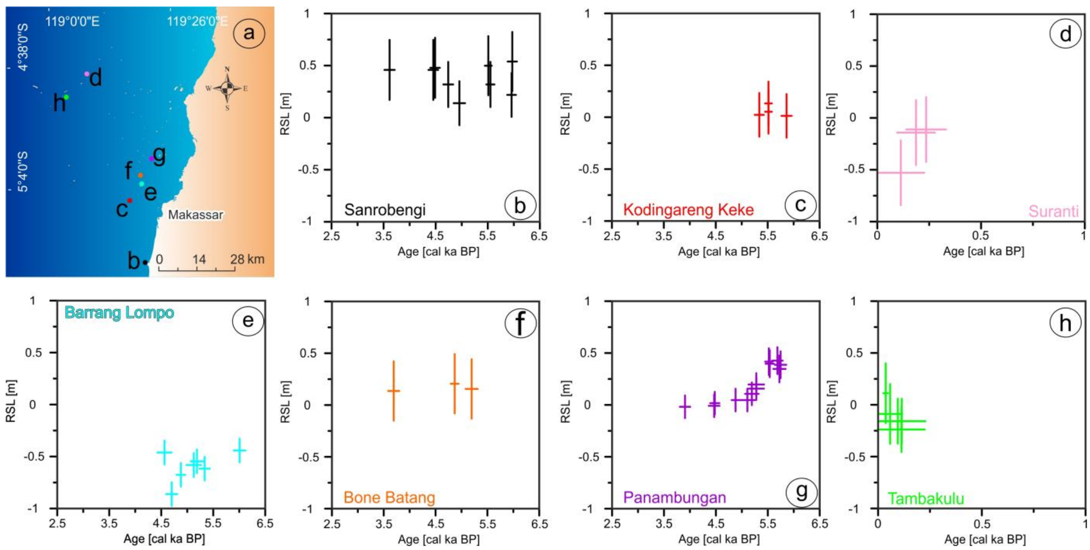

Figure 3. Holocene RSL data in the Makassar Strait. a) The locations of the islands where FMA were surveyed; panels b) to h) RSL vs age of the sea-level indicators at each island. Note that, for a better visualization and because of the young age, the x-axis for panel d) Suranti and h) Tambakulu is shorter than for the other islands, but the y-axis is unchanged.

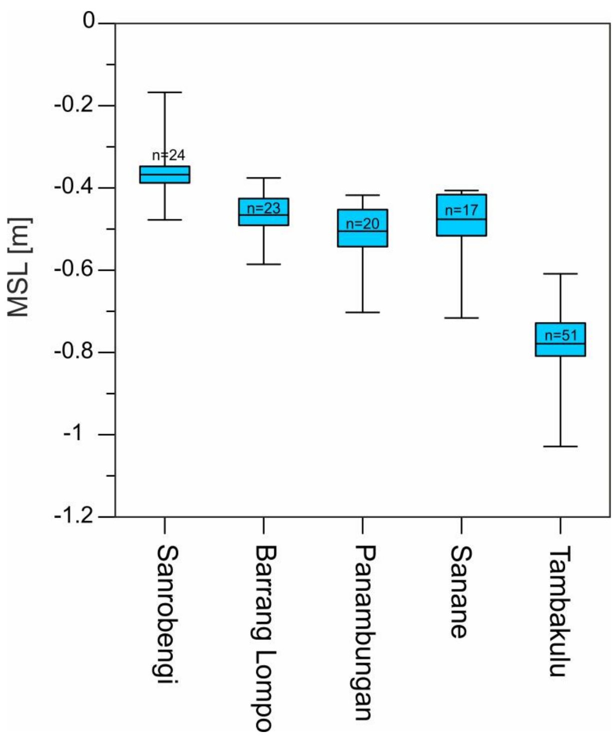

Figure 4. Box plot of the HLC elevations measured in the Spermonde Archipelago; "n"= indicates how many individuals were surveyed on each island.

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

5. Discussion

The dataset presented in Table 1 and Table 2 allows discussing five relevant points that need to be considered as Holocene sea level studies in the Makassar Strait and SE Asia progress.

5.1. Abandoning conflicting sea level histories

Additionally to our new dataset and that of Mann et al. (2016), there are two other studies reporting sea-level data for the Makassar Strait: De Klerk (1982) and Tjia et al. (1972). Both studies show a sea-level highstand in excess of 6 meters in the Makassar Strait, and only two points from De Klerk (1982) seem to be comparable with our dataset. The amassed quantity of new data agrees broadly with the observations from Mann et al. (2016) and provides further evidence that the mid-Holocene sea level highstand in the Makassar Strait was less than one meter above present sea level (Figure 6), *de facto* contradicting the studies cited above.

This raises an important question: why are the data from Tjia et al. (1972) and De Klerk (1982) significantly different from our reconstruction? A recent study by Mann et al. (under rev.) reviewed the original descriptions and interpreted these data as marine limiting points (i.e., indicating that sea level was above the measured point). This was based on the fact that the points reported in these studies are described as corals, shell accumulations, erosional terraces, oysters or mollusk deposits. These indicators might not represent valid sea level index points, and some were interpreted as marine limiting data, meaning that sea level was above the measured elevation of the geological facies reported. As a result, Mann et al. (under rev.) advise caution in using the data from older compilations in the Makassar Strait. Our dataset highlights that new studies are indeed necessary to unravel the process responsible for deposits at such high elevations as the data reported by Tjia et al. (1972) and De Klerk (1982).

One possibility, that would need further fieldwork and new stratigraphic analyses to be tested, is that these high marine deposits were emplaced by either storm or tsunami waves during the Holocene sea level highstand. For which concerns storm waves, the CAWCR wave hindcast (Durrant et al., 2013, 2015) shows that the maximum significant wave heights in the proximity of the Spermonde Archipelago reached peaks of ~4 m, with periods of ~19 s in the period 1979-2016 (Figure 5).

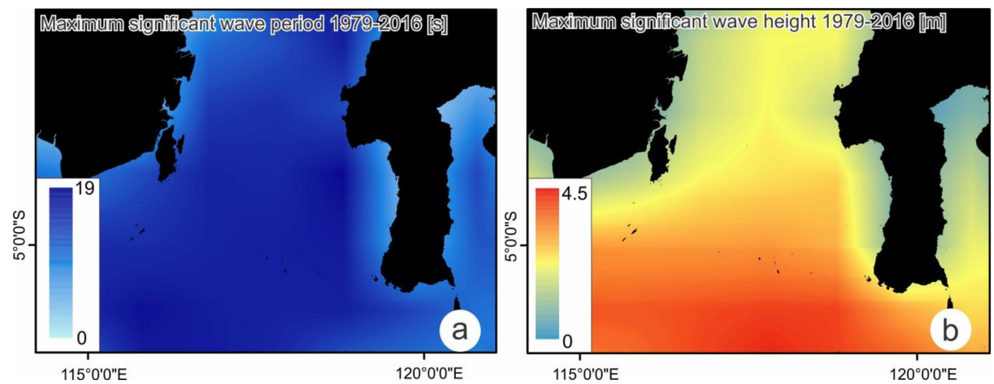

Figure 5. Maximum significant wave period (a) and height (b) extracted from the CAWCR wave hindcast (Durrant et al., 2013, 2015). CAWCR is an ocean wave hindcast that uses the WaveWatch III v4.08 wave model forced with NCEP CFSR hourly winds. Source: Bureau of Meteorology and CSIRO Copyright 2013.

Historical tsunami deposits are not unusual along the coasts of SE Asia (e.g. Rhodes et al., 2011) with the broader Makassar Strait being one of the most tsunamigenic regions in Indonesia (Harris and Major, 2017; Prasetya et al., 2001). For the center of the Makassar Strait, earthquake catalogs report only few significant earthquakes in the last ~100 years (Jones et al., 2014) and this region is considered

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

"the weakest amongst all of the seismic prone areas in Sulawesi" (Baeda, 2011). Nevertheless, three shallow earthquakes (depth below 20 km) in 1967, 1969 and 1984 generated tsunamis in this region (Prasetya et al., 2001). An earthquake on April 11th 1967 hit the town of Tinambung (140 km north of the Spermonde Archipelago) causing 58 deaths and 100 injured (Thein et al., 2014). During this tsunami, water retreat was reported but no tsunami wave height estimates are available. Another earthquake with the epicenter 215 km from the Spermonde Archipelago was reported on Feb 23rd 1969, with wave heights of 2-6 m (Prasetya et al., 2001). It is unclear whether these events may have produced significant events also in the Spermonde Archipelago: the paleo record, together with tsunami wave models for these events, may help improving the current understanding of potential tsunami risks for this area, bringing paleo constraints to it (Kench and Mann, 2017).

5.2. Validation of GIA models

Under the assumption that tectonic activity did not play a major role in the Makassar Strait (Bird, 2003; Walpersdorf et al., 1998), the bulk of data presented in this paper (except those from Barrang Lompo, discussed below) may be used to validate the outputs of GIA models. This is in turn relevant to GIA corrections applied to tide gauge and satellite measurements aimed at quantifying the modern climate-related sea-level changes.

Comparing our data with GIA predictions based on ICE-5G (Peltier, 2004) (summarized as light gray band) (Figure 6), it is obvious that the model predicts a highstand that is up to 2 m higher than the bulk of our field data, and its peak is predicted to occur roughly 1.5 ka later than what our data suggest. The ANICE model performs better in this area, also considering that it was not generated by including RSL observations to calibrate the ice model. In general, it underestimates systematically the highstand by, at worst, half meter. Overall, the best performing model across all areas is ANICE-VM3-100, which predicts a maximum highstand of 0.28 m. Standing this result, we propose that future studies should explore different ice models (associated with a larger set of mantle viscosities) to gauge better fits and misfits to our sea level index points.

The better match of ANICE to our data has a meaning for which concerns ice melting patterns. In fact, the lower highstand predicted by ANICE stems from a very different (from the nominal ICE-5G model) behavior of the Antarctic Ice Sheet (AIS) component. In ANICE, the AIS undergoes a fluctuation throughout the Holocene, which might locally interfere with the syphoning effect, hence mitigating the Holocene highstand (followed by a quasi-linear drop) predicted by ICE-5G.

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

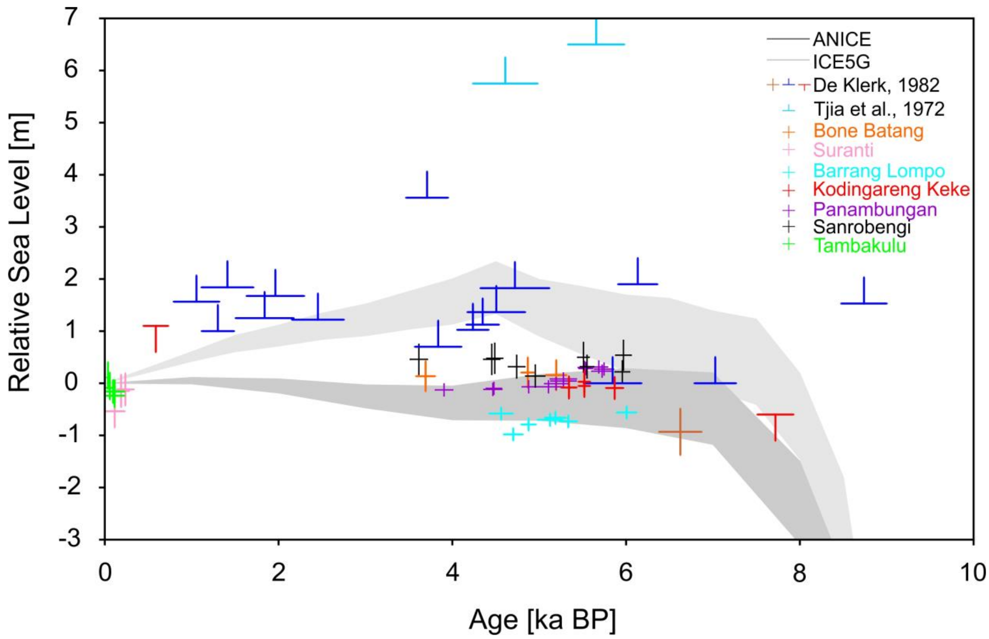

Figure 6. RSL index points, marine and terrestrial limiting data available for the Makassar Strait, including GIA model outputs. The light gray band represents GIA predictions obtained using the five iterations of ICE-5G shown in Table 1 (Peltier, 2004). The dark gray band represents GIA predictions obtained using the three iterations of ANICE shown in Table 1. The blue and light blue indicators from De Klerk (1982) and Tjia et al. (1972) indicate marine limiting indicators and the red symbol of the De Klerk, 1982 indicates a terrestrial limiting indicator. Crosses indicate sea level index points.

5.3. Measuring living microatolls

As indicated in former studies (e.g. Mann et al., 2016; Smithers and Woodroffe, 2001; Woodroffe et al., 2012) it is important to measure the height of living corals (HLC) to determine the indicative meaning of fossil microatolls. Our results demonstrate the importance of HLC being measured in a similar context to the paleo HLC. Across the Spermonde Archipelago, we observed indeed a clear geographic trend in the measured HLC (Figure 4). The highest HLC (closer to mean sea level) was measured at the southernmost island (Sanrobengi), which is also the closest to the mainland. The islands located in the middle of the archipelago (Panambungan, Sanane and Barrang Lompo) differ slightly from each other but show comparable average HLC. At Tambakulu, located further away from the mainland (~70 km from Sanrobengi), the HLC is the lowest measured.

We propose that this difference is based on a mean sea level (and possible tidal range affecting the MLLW level) difference from the coast (Makassar tide gauge) to open ocean, due to a progressively deepening general bathymetry, and there is no reason to assume that this gradient was different during the Late Holocene. Had we not taken into account this effect, our RSL estimates would have been biased. This result reinforces the importance of defining local modern analogues to calculate paleo RSL from coral microatolls (Hallmann et al., 2018; Woodroffe, 2003). We highlight that the maximum difference we found between living microatolls at different sites in our study area (i.e., ~40 cm, Figure 4) is of the same magnitude (several decimeters) with those measured at different sited by other studies (Hallmann et al., 2018; Smithers and Woodroffe, 2001; Woodroffe, 2003; Woodroffe et al., 2012). This indicates that, if no local living microatolls are measured contextually to fossil ones, there is the potential that paleo RSL reconstructions may be biased, in the worst case, by several decimeters.

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

Climate of the Past
Discussions

5.4. Local subsidence effects

As described above, the data presented in this study together with the data from Mann et al. (2016), confirm a sea level history with a sea level highstand 3.5-6 ka BP. The only exception to this pattern is the island of Barrang Lompo where microatolls of roughly the same age are consistently lower (Figure 6). Comparing the data at Barrang Lompo with those from the other islands, we calculate that, on average, Barrang Lompo RSL data is 0.8±0.3 m lower than all the other islands where we surveyed microatolls of the same age (Figure 7).

While some GIA models (specifically those not predicting an highstand in our study area, ANICE-VM1-100 and ANICE-VM2-100, see supplementary materials for details) match the lower RSL recorded at Barrang Lompo, the better matching of other models (specifically ANICE-VM3-100) on multiple islands in close proximity with Barrang Lompo (Bone Batang - 3.7 km, Panambungan - 10.8 km and Kodingareng Keke - 7.7 km) stands as a good reason to infer that Barrang Lompo is indeed subject to subsidence.

The reason for this subsidence is presently unknown, but there is one striking geographic characteristic that separates Barrang Lompo from the other islands reported in this study. Among all the islands we surveyed, Barrang Lompo is the only heavily populated one (~4.5 thousand people) (Syamsir et al., 2019). It is characterized by a very dense network of buildings and concrete docks to allow fishing boats to land. All the fossil microatolls reported in Mann et al. (2016) were located near the coast, and might have been therefore affected by subsidence due to the combined effects of groundwater extraction (at least 8 wells were reported on Barrang Lompo, Syamsir et al., 2019) and loading of buildings on the coral island. The living microatolls, surveyed on the modern reef flat few hundred meters away from the island, do not show effects of subsidence.

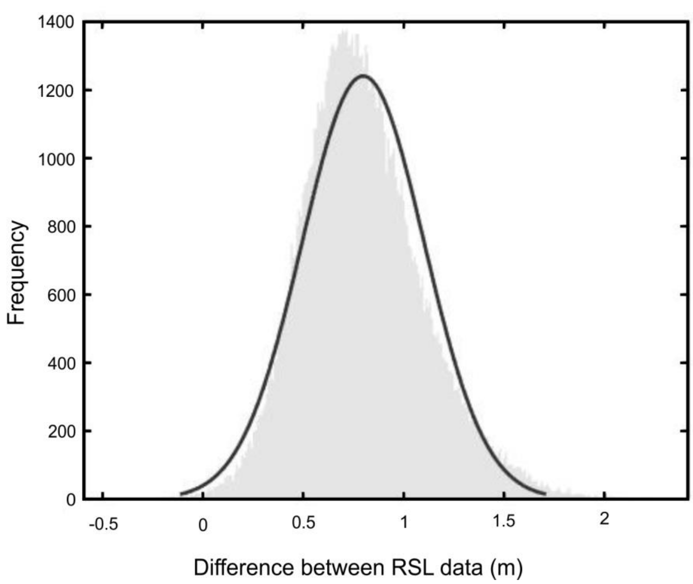

Figure 7. Difference in fossil microatoll elevations between the islands showing a Holocene sea level highstand above MSL and Barrang Lompo. For the methodology on how this figure was generated, the reader is referred to the matlab script contained in the following repository: https://github.com/Alerovere/HoloceneVerticalMovements

5.5. A Common Era sea level record from SE Asia?

One further interesting aspect of our study is that eight microatolls returned ages spanning the last four centuries. This period of time is included in the Common Era (that spans ca. the last 2 ka), that is

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

a particularly relevant time frame from the point of view of sea level changes as it marks the boundary between the tide gauge record and paleo proxies (Kopp et al., 2016). If compared with the entire Holocene, relatively few data have been published for the Common Era (1344 index points, see Supplementary Data in Kopp et al., 2016 also shown in Figure 8a). Most of these were surveyed in the US Atlantic coast and Gulf of Mexico (Figure 8d, 624 data points), while the only Common Era data in tropical areas were surveyed in the Indo-Pacific (Seychelles, Woodroffe et al., 2015) and in Pacific Ocean islands (Christmas Island, Kiribati and the Cook Islands, Goodwin and Harvey, 2008; Mcgregor et al., 2011; Woodroffe et al., 2012) (Figure 8b).

The eight data points presented in this study are, to our knowledge, the first report of Common Era data from Southeast Asia. Comparing the RSL obtained from our microatolls with the RSL by Kopp et al. (2016), we show that the elevations of six microatolls (PS_FMA2 and 3 and PT_FMA5, 6, 7 and 9) are consistent with his model, while other two (PT_FMA8 and PS_FMA1) are either too low or too high (Figure 8c). The six microatolls fitting in the modeled RSL range in elevation from -0.24±0.22 to -0.09±0.29 m. Although this comparison does not take into account the fact that our paleo RSL should be corrected for GIA, we also maintain that this is a potentially little effect over such short time scales.

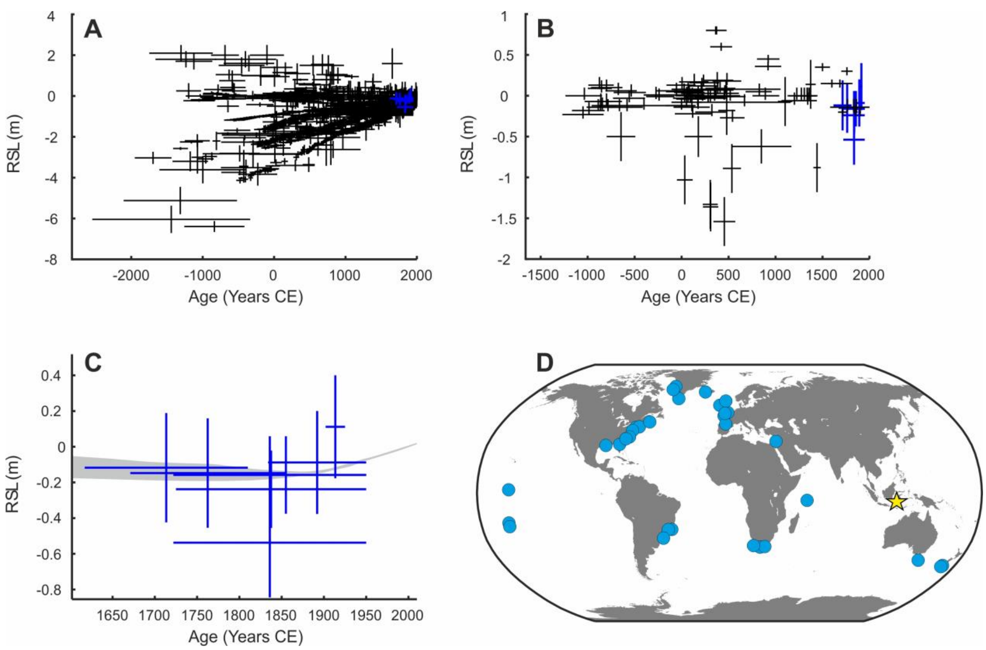

Figure 8. A) Age-elevation plot of all Common Era data as compiled by Kopp et al.(2016) (1344 data points). The blue markers indicate the Common Era microatolls dated in this survey; B) Same as in A), but limited to the data available for the Indo-Pacific and Pacific Ocean Islands; C) the eight data points reported in this study (blue markers) compared with the ML21 and ML22 models of sea level from Kopp et al. (2016); D) Location of the Common Era data compiled by Kopp et al. (2016). The star indicates the location of the study area addressed by this paper.

6. Conclusion

Our study allows us to draw few main conclusions for which concerns sea level changes in the Makassar Strait.

1. The data amassed collectively by this study and Mann et al. (2016) shows the Middle Holocene sea level highstand in the Spermonde Archipelago is less than one meter above modern sea

level. It is still necessary to find different explanations for the ~4m higher marine deposits identified by former studies in this area (De Klerk, 1982; Tjia et al., 1972). Such explanation may open new research directions in terms of paleo storms or tsunamis in this region. For which concerns GIA, the ICE-5G model modulated with differing mantle viscosities show a mismatch with our RSL results. The predicted RSL is higher than the RSL derived from our samples, and appears also shifted in time. Some iterations of ANICE seem to perform better. The differences between ICE-5G and ANICE are mainly due to a different modeling of Antarctic Ice Sheet evolution post 6 ka hence we argue that more ice and earth models should be made available to compare with our RSL data in search for a better match.

2. There is an obvious geographic trend in the Height of Living Corals (HLC) we measured on living microatolls. These HLC differences are probably based on differences in mean sea level and tidal regimes due to a changing bathymetry from the coast towards the open ocean that need to be tested via independent data (e.g. longer local tide gauge data).

3. The enigmatic low elevation of Late Holocene microatolls on the inhabited island of Barrang Lompo, already raised by Mann et al. (2016), is confirmed as an exception to a well-established pattern from other four sparsely located islands. We propose that the low elevation of these microatolls may be due to local subsidence caused by intensive human occupation of the island, with subsequent groundwater extraction. This subsidence has the potential to exacerbate, in the future, the effect of ongoing sea-level rise

4. Eight of our 24 fossil microatolls date to the Common Era. Sea-level index points of that age were found in several locations but ours are, to the best of our knowledge, the first reported for Southeast Asia. At present state, we recognize that our data are not precise enough to allow further discussion on Common Era sea level, therefore we maintain that future studies should be directed at finding more sea level indicators spanning this time frame, and measuring them with higher accuracy to allow for higher resolution sea level reconstructions.

Author contributions

MB organized fieldwork and sampling that was conducted in collaboration with TM and DK. JJ gave on-site support in Makassar. MB led data analysis, with supervision from TM and AR. TS analyzed the tidal datum and MSL; PS offered expertise, models and discussion input on Glacial Isostatic Adjustment processes. MB wrote the manuscript with inputs from AR. All authors revised and approved the content.

Declaration of Interest

The authors declare no conflict of interest

7. Data availability

The data will be available in the data repository PANGEA and we will add the DOI when the MS gets to its final stage.

https://doi.org/10.5194/cp-2019-63
Preprint. Discussion started: 20 June 2019

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