Object: Revisions of the Manuscript “Late Holocene (0-6ka) sea-level changes in the Makassar Strait, Indonesia” by Maren Bender et al.

13/03/2020

Dear Editor,

Please find attached our reworked version of the manuscript and our detailed answers to the comments of reviewers 2, 3 and 4. While we changed some points as suggested by the reviewers, we also stand by our text and ideas in some instances. Our changes to the text and rebuttals are explained in detail below.

We would like to thank the suggestions and ideas to optimize the MS by the three reviewers that helped improving the MS.

The Reviewer’s text is highlighted in gray, our answers are in plain text below.

Best Regards,

Maren Bender and the MS co-authors.

Reviewer #2 (RV2)

Line 89 – island not islands.

This was changed accordingly

Line 184 onwards – I am not totally happy with applying a modern-derived erosion value to these microatolls. What would you lose from your dataset if you removed them from your final analysis? The SLIPs with calculated erosion values (grey vertical error bars on fig 3) seem to sit systematically above the un-eroded ones. So is there a bias in your data caused by using this standard correction? Your final RSL curve would be more precise without them. I realise this would leave you with not that much to add to the Mann 2016 study, but the two sites you present with uneroded data match very well with the Mann data, which is a good thing. Another thing to consider would be to plot the eroded data completely differently (e.g. as boxes) to make it clearer that they are less certain. You also need to say something in the text about this apparent systematic offset between eroded (corrected) and non-eroded data.

We thank RV2 for this constructive comment. Of course, we could take these microatolls out of our study, but we believe that they present valuable RSL information. We believe that (also as a result of previous reviews) we labelled these microatolls clearly enough in figures, tables and in the text to present the reader an objective view on their reliability. In general, we note that the offset noticed by the reviewer is not too extreme, considering both age and elevation error bars.

Line 245 – evidence not evidences.

Changed accordingly

Line 326 – as not than.

Changed accordingly.

Fig 7 – what does Ma stand for? Why is the land black in this fig? It makes it harder to interpret than it should be!

Ma stands for Mangrove swamp. We changed the caption of the figure and included this missing information. The land is black in most modeling figures, so we are not changing it. In this figure, we indicate that land areas are filled in black color.

Line 446 – due to. I'm not sure you can compare a small island community extracting water to an Asian megacity here.

True, it is a comparison that gives an idea to the readers of the magnitude involved here, but caution is needed. So, we added this incipit to our sentence: "Notwithstanding the obvious differences in patterns and causes of subsidence".

Line 490 – most recent part not last part.

Changed accordingly.

Line 512 – delete important.

Changed accordingly.

Line 566 – use and instead of comma, and measurements instead of measurement.

Changed accordingly.
Line 592 – delete ‘which concerns’.

Changed accordingly.

Lines 602-607 – I’m not sure about the section on correcting GIA predictions using different rates of VLM. Ok so the different models require different VLM corrections, but how do you know which is correct? There is no way of knowing. You need an independent measure of VLM. Is there anything else in the coastal geomorphology that might suggest the area is subsiding or uplifting long term? I don’t think you can leave this section as it is without making some attempt to validate your conclusions (or you need to state more clearly that either positive or negative VLM is equally likely).

Unfortunately, other than the GPS stations cited (that are at odds with each other), we do not have any hard constraints on VLM. Many authors consider this area “stable”, but we felt that this would be too simplistic in absence of clear indications. For this reason, we kept the paper open. We hope that, by restructuring the last part of our conclusions, our rationale is more clear.

Reviewer #3 (RV3)

Overall, authors do not clearly define the main impetus for this work nor do they offer specific insight into future research directions, implications of results for the Holocene sea-level history beyond the Spermonde Archipelago.

We thank RV3 for this comment and point out, that indicating future sea-level predictions or setting this new data in a broader context is not the aim of this study. The aim of the study is to show new data from the Spermonde Archipelago and compare this new dataset with previous studies from the same location and new GIA models, to unravel the existing inconsistencies in the RSL history between the three studies and to widen the knowledge of the RSL history in this rarely studied region.

It is not clear until the conclusion that the purpose of the GIA model-data comparison is not to identify glacio-eustatic contributions to late Holocene sea-level nor to investigate the evolution of late Holocene sea-level but to identify a best-fitting GIA model that could be used to refine predictions of current and future sea-level trends. A best-fitting model is ultimately not identified, nor are future directions. I therefore recommend major revisions to this manuscript to improve clarity.

We tried to streamline the last part of our conclusions also taking into account this comment.

The introduction does not establish why it is important to reconstruct sea-level changes during the Holocene, a time of transition between glacial and interglacial climates, nor does it emphasize why SE Sulawesi was selected for analysis, the power of microatolls as a proxy for past sea-level position on multiple timescales, and why evaluating data in the context of GIA model reconstructions of past sea-level is critical to evaluating global mean sea-level from local sea-level reconstructions in the past and the present.
We generally explain the importance of Holocene sea-level studies in the lines 55-63 and further, SE Sulawesi was not selected as study region. We further decided to explain the use of microatolls as sea-level index points and the use of GIA models in the methods. We decided, that technical things like these are better placed in the methods part, subdivided into their own topics, which isolates the

introduction from the methods and gives the reader the chance to first indicate what this paper is about and then see how we conducted our study.

While the sea-level index points are combined with 3 previous studies from the vicinity of Makassar, there is no discussion of the results in the context of Late Holocene sea-level reconstructions from SE Asia and the South Pacific (e.g. Hallmann, 2018), or other Holocene SL reconstructions derived from microatolls.
We agree with RV3 that we did not discuss and compare our study and the studies from Mann et al., 2016, De Klerk, 1982 and Tjia et al., 1972 to other studies from the broader region of SE Asia and the South Pacific. It was our aim to compare only studies from the same region, to extend the RSL information in this location and to evaluate if the data from De Klerk and Tjia agrees or disagrees with our new data. It was not the aim to compare the new data from the Spermonde Archipelago to entire SE Asia and the southern Pacific region as this was already done by Mann et al., 2019 who indicated different data inconsistencies in several locations in SE Asia where the Spermonde Archipelago, (due to the data from De Klerk, Tjia et al and Mann et al., 2016) is one of these regions that needed more high-quality data (our study) to improve the knowledge of the local Holocene RSL history. A quote is mentioned in line 352 to 355.

How do RSL results compare with other reconstructions and what are the limitations of the previous works? As written, it does not seem to be anchored to a clear history of previous work (regional, global, Holocene) for readers to critically evaluate the importance and significance of the results that it presents, nor is it framed as novel or distinct form previous work in terms of its methods, study site, etc other than the introduction of new index points and extensive GIA modeling.
This analysis that is asked for in this comment, was already published by Mann et al., 2019 and is therefore not the aim of this study. In Mann et al., 2019 only three GIA models were compared to the different data sets, also to the 3 sets from the Spermonde Archipelago and we aim to extend this dataset with new data and a higher amount of GIA model outputs to improve the RSL history in this study area. It was a successful study as we can support the data by Mann et al., 2016 and discuss new reasons for the inaccuracy of the dataset from De Klerk, 1982 and Tjia et al., 1972. Further, we improved the previous studies in this location by a comparison to more GIA model outputs and can implicate that tectonic is not the reason for the difference in the RSL elevation results.

I would restructure the first 75% of the introduction as follows:

1. Statement on importance of reconstructing Holocene ice-sheet and sea-level response to an interglacial climate. Succinctly state why this is relevant to accurately and precisely predicting timing and rates of future ice-sheet and sea-level response to the present warming climate. Why are you presenting new Late Holocene sea-level data and GIA models?
2. Briefly, describe state of knowledge from far-field, Indo-Pacific Holocene sea-level reconstructions – any trends or outstanding questions. Why are far-field records important? How you reconstruct sea-level index points using microatolls and what are their advantages/disadvantages relative to other sea-level indicators?
3. How do you expect GIA to influence local sea-level histories in this region and why it is necessary to correct local sea-level histories for the influence of GIA and vertical land motion due to tectonism in ordered to evaluate glacio-eustatic sea-level changes? As you already mention in the introduction, determining rates of subsidence/uplift due to regional tectonics by accurately estimating past sea-level is a circular problem discussed at length in Creveling et al. (2015). *
4. Why was SE Sulawesi selected for analysis and what steps did you take (as written) to generate an accurate RSL reconstruction?

While we thank RV3 for this suggestion, we decided to make only minor changes to the introduction. About 1), we say briefly why this kind of study is important in the second paragraph of the introduction. A reviewer of the former version suggested us to downplay the “past for future” angle, so we will keep our rationale as it is now. About 2), most of the description the reviewer is asking is shifted to the first section of the methods. This was also done in response to a previous round of review. About 3), we also tried to insert some considerations on this point in the second paragraph of the introduction. About 4), we address this point in the first section of the “Regional Setting”. It was shifted there after a previous comment from a reviewer, so we will not shift it to the introduction.

Definitions: In the intro, define terms such as relative (local) sea-level (RSL) (Line 49), and what you mean by “eustatic” sea-level (Line 45 vs 50).
We slightly restructured the first paragraph of the introduction to clarify what is eustatic and what is local sea level. We assume that readers of Climate of the Past will have a training in geoscience/climate science, so this brief reminder of concepts is enough, without entering detailed descriptions of eustatic and relative sea level concepts that are widespread in the literature.

On Line 45, you describe “globally averaged” sea-level, or GMSL (which is includes contributions from thermal expansion and changes in global ice-volume), but elsewhere (e.g. Line 50) you use “eustatic” to describe “glacio-eustatic” or “ice-equivalent” changes in sea-level in response to transfer of mass between ice and ocean (Mitrovica and Milne, 2002; Milne, 2015 *Handbook of Sea-level Research*, citations therein). It is my understanding that all three of the phenomena listed in Lines 51-54 to explain the common observation that far-field sea-level reconstructions record a mid-Holocene highstand fall under the definition of GIA (see concise explanation of equatorial syphoning/GIA trends and in Dutton et al, 2015 *Science* in addition to Kopp et al., 2015, Mitrovica and Milne 2002, Milne and Mitrovica 2008, etc.). GIA processes include deformational, gravitational and rotational effects driven by the transfer of mass between ice and ocean that can cause local RSL changes to depart significantly from the GMSL curve or the response of the solid Earth and gravity field to the climate-driven surface ice- water mass redistribution (Milne and Shennan, 2013). Syphoning, changes in gravity due to surface ice-water mass redistribution and solid Earth deformation are all driven by GIA
We modified our wording to make it more clear that GIA includes syphoning and rotational feedbacks. Thanks for pointing this out.

Line 44: I think that sections must be numbered. https://www.climate-of-the-past.net/for_authors/manuscript_preparation.html
We defer to the copy-editing process of Climate of the Past for this aspect.

Line 56: You repeat the definition of the RSL acronym again.
Thanks, we changed the text accordingly, and keep using the acronym.

Line 65: To reconstruct paleo RSL, we measured the age and elevation of microatolls, ie…Line 71: fossil ones, that we surveyed and dated using radiocarbon.
Accepted

Methods:
Lines 119 – 131: A conceptual figure or a reference to one may be useful here to visualize how microatolls are used as a proxy and linked to tidal datums, indicative range, etc. in this study.
In the section “coral microatolls” we make extensive reference to the most widely cited (and recent) literature on microatolls.

Line 124: Please be more specific about what you mean by “extended periods of time” perhaps relative to the growth rate of the coral?
We deleted the reference to “extended periods of time”.

Line 130: Please be specific about what you mean by short-term sea-level fluctuations.
Decadal to centennial, fixed in the MS.

Line 140 – 141. This is an important point.
We thank RV3 for this comment.

Line 141: Clarify your definition of indicative meaning.
Following this comment, we decided to give a brief hint to what the indicative meaning is directly in this sentence. We then give a proper reference in the first lines of the "Paleo RSL calculation" section. There, we expanded the indicative meaning description with respect to the previous version.

Lines 117-141 General comment: Methods are clearly outlined. Assumptions made in using microatolls to reconstruct sea-level are not (e.g. as referenced in McLean et al., 1978). What assumptions go into assigning a reference water level to the coral's highest level of survival? Is the relationship between microatoll elevation and tidal cycle the same over time and across areas of the reef? Are all microatolls morphologically similar here and why is this a good field site?
The use of microatolls as good sea-level indicators is an accepted RSL measurement method by the sea-level community and explained or discussed in several previous publications, where some are cited in the previous section. We think that re-explaining the use of Microatolls for paleo RSL reconstructions would be redundant and out-of-scope for this MS. We further explain that the relationship between the microatoll elevation and the tidal cycle deviates due to site-specific characteristics, thus living microatolls should be used as modern counterparts to adjust fossil microatolls to the modern height of living coral and thus make sure living and fossil microatolls in the same site grew within similar conditions. We think this answers the question "Are all microatolls morphologically similar here?". With the HLC survey method, we exclude RSL elevation errors due to variabilities in the morphology of microatolls between the different study sites. The last question "why is this a good field site?" are indirectly answered in the "Regional setting" section, where we explain why this region is important to study.

Line 143: FMA's and LMA heights are the maximum (peak) height of the microatoll, correct? Or is it the average elevation surveyed across the top of the microatoll?
Yes, we always surveyed the highest rim of the microatoll. We clarified this in the MS.

Line 167: Replace reducing with relating.
We changed this word accordingly.

Line 177: How far away were these islands? Did you consider potential variations in the height of the geoid as per Woodroffe et al. (2012)?
Yes, we considered potential variations and checked the Geoid for differences, but published models do not show any appreciable variation.

Lines 204-222: Please explain further in the section on sampling and dating what kinds of samples you selected (slice of the microatoll? Hand samples?) and where you sampled from on the microatoll (the highest point on the microatoll or across it?).
We added a short explanation to this effect at the beginning of the sampling and dating section.

In general, how did you assign a radiocarbon age to a microatoll? Was there one date per microatoll or did you measure multiple dates to interpret an age (see distinction for U-series in Dutton et al., 2017)?
We obtained one age per microatoll, we clarified this point in the "Sampling and dating" section.

Additionally, please clarify what diagenetic screening you employed when analyzing coral preservation in advance of radiocarbon dating and report your XRD results (see more on XRD reporting in Vyverberg et al., 2018).

We dated corals with very high aragonitic content. We added a small section to the results to describe some samples affected by the presence of calcite, and we added the results of the XRD analysis to the Supplementary Material.

This information may also be useful in light of the documented erosion for most fossil microatolls in this study. Clarify your reference age for (a BP) – is the present defined as 1950 CE?
There is no need to clarify the BP convention, where 1950 is present.

Line 223: Please clarify here or in methods why you are predicting RSL with GIA modeling.
We believe that it is a very standard approach to predict RSL with GIA models and compare it with observed data. We added a short clarification at the beginning of the "Glacial Isostatic Adjustment" to avoid confusion.

Later, in the discussion, perhaps touch on the following: *Do you intend to convert RSL to GMSL via the extraction of the GIA signal at this location? Can any inferences of GMSL be made here? What steps would be needed to determine GMSL from your RSL results, and what are the challenges faced in converting RSL to GMSL via the extraction of the GIA signal at this location? Why don't you attempt to remove the GIA signal - provide clarification (e.g. further discussing implications of Fig. 11) as to why not. Elaborate on why evaluating GIA matters for Holocene/modern sea-level reconstructions and what the limitations to evaluating the GIA signal are here or in general.
The line of discussion was carefully selected in order not to overinterpred our data. Calculating GMSL from our data, with all the uncertainties embedded (VLM and GIA) would produce a spurious result, which would be of little interest.

Results:
Line 240: I see now that these are average radiocarbon ages as opposed to raw dates. I would clarify how many samples (dates) were analyzed to determine an age and how that data was evaluated for diagenetic alteration.
Our choice of words was odd. We dated 25 fossil microatolls and received one age per microatoll as explained earlier. We clarified also in this section.

Line 178, 248, 551: Please revise phrasing of "For which concerns" to "concerning **…"**
We rephrased these parts accordingly.

Line 240: Table 2: Following the equation on line 172, RSL estimates in Table 2 appear to be off by ~ 0.01 – 0.02 m. (ex – PS_FMA1 Suranti: RSL = -1.46 – (-0.74) + 0.2 = -0.52 m. In Table 2 it is reported as -0.53 m and using the numbers in Sheet 9 of SM1 RSL = -0.54 m. The excel sheet reads -0.53m using whatever rounding rules were applied in excel and the data correction of +0.014m. Furthermore, the Reference Water Level reported in SM1 is not always comparable to that reported in Table 2. For Suranti and Tambakulu it is as -0.72 m in SM1 but reported as - 0.74 in Table 2. Please address rounding and reporting discrepancies.
This was probably a glitch that remained from a previous version. Now SM and tables in the text coincide.

Table 3: Why is erosion error not included in Table 3, when it is included in SM1 Sheet 4 for FMA8 – 11 (Panambungan)? The erosion factor seems to be incorporated into RSL for those points in Table 3; without it the RSL values calculated in Table 3 are lower by 0.2m.
FMA 8-11 were published in Mann et al. The erosion error was already included in the original paper. As we took their elevation values for both LMA and FMA, we decided to keep them as they were provided. We wanted to visually separate our data table from the tables containing data from the other authors and therefore did not split the elevation calculation and used the elevation data as it was given by the original papers.

Discussion:
Line 318: Please clarify by how much HLC changes instead of “HLC changes substantially.”
We changed the sentence to avoid the word “substantially”

Line 345: I would mention what “sea-level data” refers to. It is only mentioned in the caption of Figure 7 that the earlier works used different sea-level proxies.
We changed “sea level data” into “paleo sea-level observations”. This should clarify what we mean.

Line 349: Be careful about the use of “significantly” here and throughout. Is the difference statistically significant?
No, it is not statistically significant but there is a big difference in the elevation results. To make this clearer we substituted “significantly” with “conspicuously” in this line.

Line 358: I would elaborate on the differences between the proxies used in these different studies. How does the precision vary between them? Looking at the uncertainty bars in figure 3, the De Klerk and Tjia sea-level index points tend to be higher than those reported in Mann and this study, but they are also less precise. Several points from this study/Mann fall within the bounds of vertical error for points from De Klerk and Tjia.
De Klerk published only one index point and Tjia et al. only report limiting data points. Figure 3 shows that these marine and terrestrial limiting indicators are, by definition, less precise than the index points presented by Mann et al and in this study. Thus, the difference is: these marine/ terrestrial limiting points presented by the two studies give only limiting indications on sea level, and cannot be equated to index points. In our criticism of these older datasets we address these points.

Line 368: What additional data would need to be explored to evaluate the tectonics hypothesis?
To clarify, we changed this sentence into: “While this is a possibility that would need further paleo RSL data to be explored (expanding the search of RSL indicators beyond the islands of the Spermonde Archipelago) [...]”

Line 373: Are the De Klerk coral data collected from coral in growth position? (in situ)
There is little information on these deposits, they were published long ago and reporting standards have changed since. Details for the coral at Tanah Keke do not allow to assess whether it is in situ or not. For the other corals and shells, they seem more to be described as ‘accumulations’ so not in situ.

Lines 519 – 560. It is to be expected that there is a range of highstand predictions that vary in space and time depending on GIA model ice and earth parameters, and it is clear that the fit between predicted and observed RSL also varies depending on the GIA model parameters as well as the assumed tectonic history. Is the main takeaway that the ICE5g model is not a good fit because, regardless of the tectonic history, the peak highstand predicted by ICE5g does not match the peak in the observed RSL data? What is the main outcome of this data-model comparison, or what steps can be taken to better compare them in future studies? The purpose of this comparison was not clearly defined in the first place, though the importance of identifying GIA models that best fit Late Holocene data to improving model predictions of current and future sea-level changes is explained on line 553.
We tried to streamline the last part of our conclusions also taking into account this comment.

How does the choice of GIA model affect the interpretation of RSL index points made in this study? What can the reader conclude about late Holocene sea-level form the data-model comparison described in these latter sections and the earlier comparison of data between this and previous RSL reconstructions? See previous comments on line 223 regarding inferences of GMSL at this location.
The choice of GIA models does not affect in any way the interpretation of RSL index points, and we believe that this is very clear in the paper.

The discussion of Late Holocene RSL and Fig. 12 seemed to end abruptly. Please elaborate on why the results in Fig. 12 are widely relevant to modern sea-level estimates.
We added an explanation at the end of the section, providing an example.

Line 572: Specify a gradient in elevation
This was extensively discussed above, we feel it would be redundant to repeat it here.

Figures:
General comment: All figures have simple and elegant layouts. Fonts are legible and colors are clear. Sections are clearly marked and figures are overall helpful and easy to follow.
We thank the RV3 for this comment.

Figure 1: in 1b, I would not combine red and green-colored dots to make the figure accessible to color-blind readers. Perhaps try a dark boarder to yellow dots in c – i to make them more legible.

Figure 3a: Have you tried making the symbols slightly different between datapoints from this study and from Mann? As mentioned earlier do not include red/green together.
We would rather not change the symbols, as they represent a standard for sea level studies. We changed the colors.

Figure 4a: I would identify the sites analyzed in this study with a (*) next to the name. Specify in the caption at least once that you mean individual microatolls instead of "individuals."
It is not clear what the reviewer means by "sites analysed in this study". We specified that we studied single microatolls in the caption.

Figure 5: Change Red/Green combination.
Done.

Figure 11: Change Red/Green combination. The four boxes in this figure are missing panel letters (a – d).
Done

Figure 12: I would mark the position of the Spermonde Archipelago on the map for reference.

Done

Reviewer #4 (RV4)

Authors critically re-evaluated reported index points by De Klerk (1982) and Tjia et al. (1972) and suggested to reconsider sediment interpretation as high-magnitude storm deposits and until further field investigation exclude them from sea-level compilations.
I also carefully reviewed authors' responses to comments by two anonymous reviewers and concluded that the manuscript was significantly improved since its original submission and that authors critically addressed reviewers concerns and suggestions.
We thank RV4 for this summary and comment.

I suggest that the manuscript will be considered for publication after few minor revisions.

1. In the Abstract authors state that they are reporting 24 new index sea-level points (line 38). However, in the Conclusion the authors report 25 index points (line 556). It is my understanding, that microatoll PB-FMA 4 index point was rejected. Please clarify.

This is true and we added the information that one index point was rejected to the sentence.

2. I suggest to add indexes “a” and “b” to the panels on Figure 8 to be consistent with other figures format.

We agree with RV4 and changed the figure and the capture accordingly.

3. I suggest to add indexes a, b, c, d to Figure 11. Text references to Figure 11 have already include the appropriate indexes (lines 530, 535, 539, and 542).

   We thank the RV4 for this suggestion and changed the figure panels and the caption accordingly as we simply missed this.

In addition, I agree with R1’s comment 2 regarding the anthropogenic subsidence on Barrang Lompo island being the major reason for a low rate of sea level rise. Since the instrumental data to support the proposed hypothesis does not exist, authors suggest that high rate of coastal erosion on the island could be indirect evidence of human impact and propose to further investigate this idea or leave the question open inviting other plausible explanation of the low rate that mismatch the regional sea level trend.

We take this comment as an approval of our choice to leave the discussion on this point open.

In the summary, I believe that the manuscript presents valuable data and paleo sea-level reconstruction using best-fit GIS model and is suitable for publication in CP. Analysis of ice models beyond the study area empathizing the need for GIA correction as essential for estimate of eustatic sea-level changes and future predictions presents an interest to a broader scientific community

Again, we thank RV4 for this comment.

Late Holocene (0-6ka) sea-level changes in the Makassar Strait, Indonesia

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Keywords: Makassar Strait, Spermonde Archipelago, Holocene, Sea Level Changes

Abstract

The Spermonde Archipelago, off the coast of Southwest Sulawesi, consists of more than 100 small islands, and hundreds shallow-water reef areas. Most of the islands~~them~~ are bordered by coral reefs that grew in the past in response to paleo relative sea-level changes. Remnants of these reefs, deposited in the Late Holocene, are preserved today in~~I~~ ~~the~~ form of fossil microatolls. In this study, we report the elevation, age and paleo relative sea-level estimates derived from fossil microatolls ~~for~~ surveyed in five islands ~~in~~ of the Spermonde Archipelago. We describe 24 new sea-level index points ~~from fossil microatolls~~, and we compare our dataset with both previously published proxies and with relative sea-level predictions from a set of 54 Glacial Isostatic Adjustment (GIA) models, using different assumptions on both ice melting histories and mantle structure and viscosity. We use our new data and models to discuss Late Holocene relative sea-level changes in our study area and their implications in terms of modern relative sea-level estimates in the broader South and Southeast Asia region.

Introduction

After the Last Glacial Maximum, eustatic sea level (i.e. global mean sea level, Rovere et al., 2016) rose as a result of increasing temperatures and ice loss in Polar regions. Rates of sea--level rise due to ice melting and thermal expansion (i.e., eustatic) progressively decreased between 8 to 2.5 ka BP (Lambeck et al., 2014Lambeck et al., 2014), remaining constant thereafter (until the post-industrial sea--level rise). Sea-level reconstructions iIn areas far from Polar regions (i.e., far-field, Khan et al., 2015) show a the rapid eustatic sea-level rise after the Last Glacial Maximum after the onset of the Holocene (~12 ka BP)was, followed by a local (i.e., relative) sea- level highstand in many equatorial areas between ~6 and ~3 ka BP, and a subsequent sea-level fall towards present-day sea level. It has been long shown that the higher-than-present relative sea level (RSL) in the middle Holocene (e.g. Grossman et al., 1998; Mann et al., 2016) is not eustatic in origin, but was caused by the combined effects of glacial isostatic adjustment (GIA) (Milne and Mitrovica, 2008), that that includes ocean syphoning (Milne and Mitrovica, 2008; Mitrovica and Milne, 2002; Mitrovica and Peltier, 1991) and and redistribution of water masses due to changes in gravitational attraction and Earth rotation following ice mass loss (Kopp et al., 2015).

Following Due to the spatio-temporal variability of these the processes causing it, the Late Holocene highstand differs regionally in both time and elevation. The occurrence of RSL indicators deposited during the highstand is dependent not only on the processes mentioned above, but also on the magnitude of Holocene land-level changes due to geological processes, such as subsidence resulting from sediment compaction or tectonics (e.g., Tjia et al., 1972; Zachariasen, 1998). Within this contextUsing precisely measured and dated RSL indicators in areas where the highstand occurs has the potential , understanding to Late Holocene sea-level histories is essential to improve our knowledge on current long-term rates of land-level changes, which need to be considered in conjunction with local patterns and rates of current eustatic sea-level rise (e.g. Dangendorf et al., 2017) to gauge the sensitivity of different areas to future coastal inundation.

In this study, we present new Late Holocene sea-level data and GIA models from the Spermonde Archipelago (Central Indonesia, SW Sulawesi). To reconstruct paleo RSL we surveyed microatolls, i.e. particular coral morphologies forming in close connection with sea-level datums such as Mean Low Water (MLW) and Lowest Astronomical Tide (LAT) (e.g., Scoffin and Stoddart, 1978; Woodroffe et al., 2012; Woodroffe et al., 2014). To improve the accuracy of our paleo sea-level reconstructionsreconstruct paleo RSL, we first studied living coral microatolls to calculate the range of depth with respect to mean sea level (MSL) where corals are living at different islands. We then applied the results of the living microatolls (LMA) survey to fossil ones, that we surveyed and dated using radiocarbon.

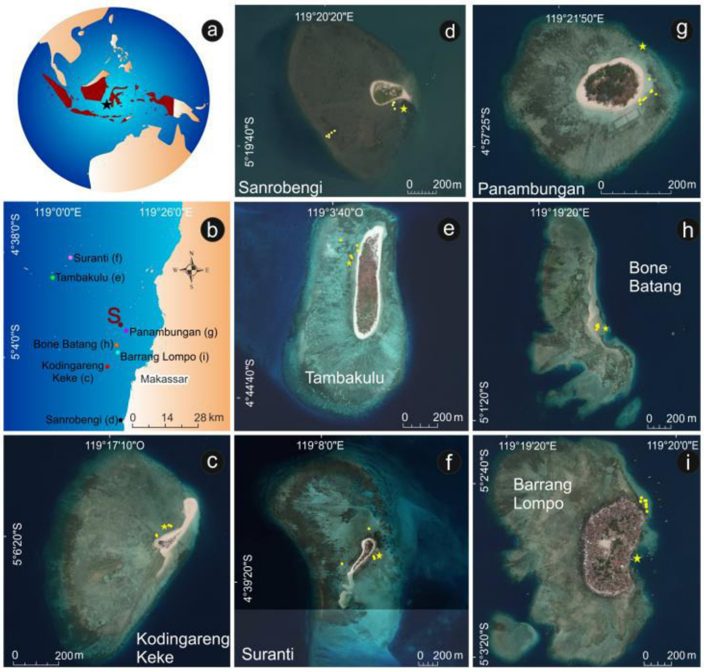
In total, we surveyed 24 fossil microatolls (FMA), with ages are clustered around ~155 and ~5000 years Before Present (BP). We presentuse this new dataset, in conjunction with data presented provided by previous studies in the same region (Mann et al., 2016; Tjia et al., 1972; De Klerk, 1982) and new GIA models with varying ice histories and mantle properties. We use our data and models to , to discuss Late Holocene relative sea level changes in SW Sulawesipossible local subsidence mechanisms at one heavily populated island (Barrang Lompo), vertical land movements in the broader Spermonde Archipelago and implications of the different ice and earth models for modern sea level estimates.

Regional Setting

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 several low-lying islands, with average elevations of 2 to 3 m above mean sea level (Janßen et al., 2017; Kench and Mann, 2017). All these islands consist of table, platform, patch reefs crowned by coral cays fringing reefs bordering sand and rubble accumulations (Sawall et al., 2011) and

Commented [AR1]: Please add to citation list: https://www.pnas.org/content/111/43/15296 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, inundation by waves and deficits in sediment supply (Kench and Mann, 2017). In the Spermonde Archipelago, the tidal cycle is mixed semi-diurnal with a maximum tidal range of 1.5 m (data from Badan Informasi Geospasial, Indonesia).

In this study, we focused on five islands in the Spermonde Archipelago. Here, we surveyed fossil microatolls that are complementary to those previously surveyed at two other islands in the same archipelago, reported in Mann et al. (2016) (Figure 1~~Figure 1~~a, b). **Panambungan** (RSL data in Mann et al., 2016) (Figure 1~~Figure 1~~g) is a small and uninhabited island, located 18 km northwest of Makassar City. **Barrang Lompo** (RSL data in Mann et al., 2016) (Figure 1~~Figure 1~~i) is located 11.2 km northwest of Makassar and 11 km southwest of Panambungan, and is densely populated. **Bone Batang** (Figure 1~~Figure 1~~h) is a narrow, uninhabited sandbank located south of the island of Panambungan and north of the island of Barrang Lompo. South of Barrang Lompo, and 13 km southwest from the city of Makassar, we surveyed **Kodingareng Keke** (Figure 1~~Figure 1~~c), another uninhabited island. 25 km south of Kodingareng Keke lies the island of **Sanrobengi** (Figure 1~~Figure 1~~d), a small, sparsely inhabited (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 1~~Figure 1~~f) and **Tambakulu** (Figure 1~~Figure 1~~e) 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. The exact coordinates of the islands mentioned above are provided in SM1.


a
b
119°0'0"E
119°26'0"E
4°38'0"S
5°4'0"S
Suranti (f)
Tambakulu (e)
S
Panambungan (g)
Bone Batang (h)
Barrang Lompo (i)
Kodingareng
Keke (c)
Makassar
Sanrobengi (d)
0
14
28 km
c
119°17'10"O
5°6'20"S
Kodingareng
Keke
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200 m
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119°20'20"E
5°19'40"S
Sanrobengi
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200 m
e
119°3'40"O
4°44'40"S
Tambakulu
0
200 m
f
119°8'0"E
4°39'20"S
Suranti
0
200 m
g
119°21'50"E
4°57'25"S
Panambungan
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200 m
h
119°19'20"E
Bone
Batang
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Lompo
5°3'20"S
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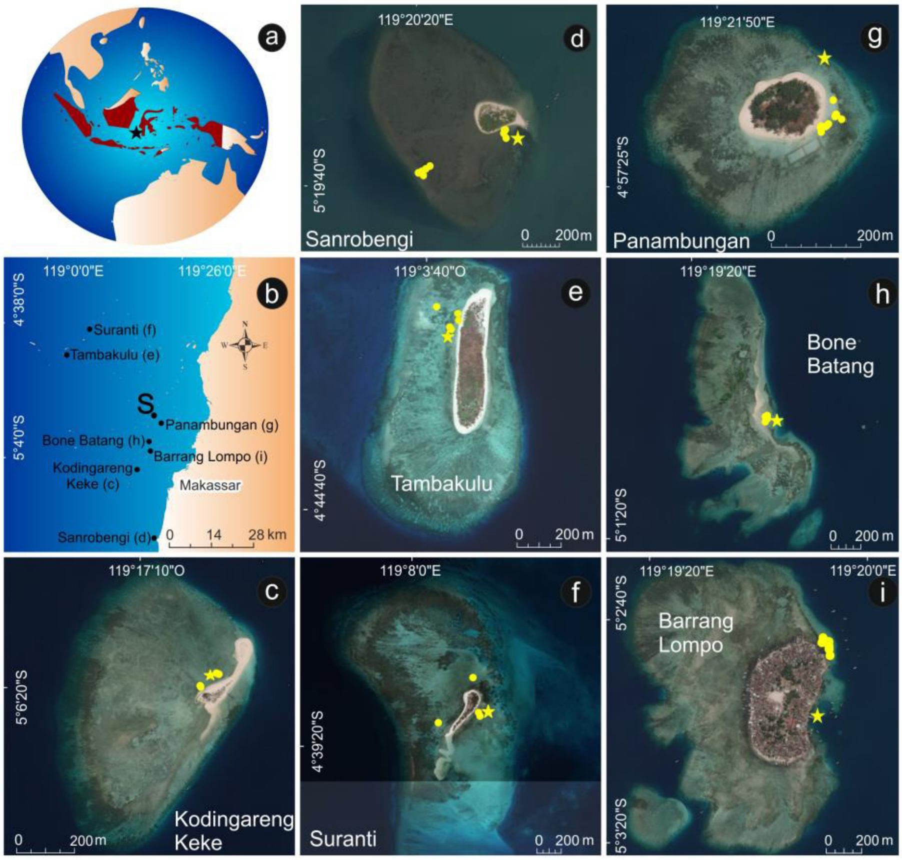

Figure 1: Overview map of the islands investigated in this study and the two islands studied by Mann et al. (2016) (Panambungan and Barrang Lompo). The star in a) indicates the location of the Spermonde Archipelago, off the coast of southwestern Sulawesi; b) indicates the position of each island, with the red dot labelled "S" indicates the position of Sanane, where only living microatolls were surveyed. Insets c) to i) show each island. The yellow dots in these panels 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.

Methods

Coral microatolls

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 and Webster, 2014). In the most standard definition, microatolls live at Mean Lower Low Water (MLLW), but their living range can span from Mean Low Water (MLW) down to the Lowest Astronomical Tide (LAT) (Mann et al., 2019). In general, this restricted range of formation reflects the fact that microatolls grow upwards until their polyps reach MLW, and successively keep growing horizontally at the same elevation. If sea level ~~rises above the MLW or~~ falls below LAT ~~over extended periods of time~~, the coral polyps die, retaining their fossil skeleton only (Meltzner and Woodroffe, 2015). 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 a narrow range (Meltzner and Woodroffe, 2015). Fossil microatolls can also be assigned an age, either by ^{14}C (Woodroffe et al., 2012) or U-series dating (Azmy et al., 2010). Recent studies 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 (e.g. decadal to centennial) sea-level fluctuations (Meltzner et al., 2017; Smithers and Woodroffe, 2001; Kench et al., 2019).

While the relationship of coral microatolls with the tidal datums described above is often maintained, several authors (e.g. Mann et al., 2016; Smithers and Woodroffe, 2001; Woodroffe et al., 2012) pointed out that deviations from microatoll living range and tidal datums may occur due to site-dependent characteristics, such as wave ~~regime~~intensity, tidal ranges and broader reef morphology (Meltzner and Woodroffe, 2015). It is also worth highlighting that a tide gauge with long enough time series might not be available at remote locations where microatolls are often found. Therefore, it is both more practical and more accurate to reconstruct paleo RSL at the time of microatoll life starting from the height of living coral microatolls (Height of Living Coral microatolls, HLC). This allows determining the paleo RSL associated to fossil microatolls that were living on the same geographical setting as modern ones (i.e., the same island or group of islands). For this reason, in this study, we sampled both fossil and living microatolls elevations, and we determined the indicative meaning (i.e., the correlation with sea level) of the fossil microatolls from the HLC rather than to tidal datums.

Elevation measurements

Fossil and living microatoll (respectively, FMA and LMA) heights were surveyed on Sanrobengi, Kodingareng Keke, Bone Batang, Suranti and Tambakulu (Figure 1~~Figure 1~~c–i) with an automatic level. FMA~~L~~ and LMA heights were always taken on the top microatoll surface. ~~Their e~~Elevations were initially referenced to locally deployed water level sensors (Seametrics PT2X) acting as temporary benchmarks. Locations of water level loggers are shown as stars in Figure 1~~Figure 1~~c–i, and logged water levels are reported in SM1. These sensors were fixed to either jetties or living corals close to the survey sites and logged the tide levels at 30-second 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 (1.1.2011 – 19.12.2019, data courtesy of Badan Informasi Geospasial, Indonesia) to establish the reference of our sample sites to MSL. As a result of annual sea~~-l-~~level variability, the mean tidal level at Makassar during our surveys was slightly above (+0.014 m) the long-term MSL (1-Jan-2011 to 19-Dec-2019). Our elevation measurements were corrected accordingly.

FMA and LMA measurement error was propagated using the root mean square of the sum of squares of the following values (see SM1 for calculations and details):

- Automatic level survey error = 0.02 m, as in Mann et al. (2016). If the automatic level had to be moved due to excessive distance from the benchmark to the measured point, this error is added twice.
- Error referencing island logger to Panambungan MSL. This error has been calculated comparing water levels measured at each island against those measured at Panambungan, and varies from 0.01 to 0.07 m (see SM1 for details)
- Error referencing Panambungan to Makassar MSL = 0.04 m, as in Mann et al. (2016).
- Error in calculating Makassar MSL from a limited time (8.9 yrs, 1-Jan-2011 to 19-Dec-2019) and not for an entire tidal cycle (18.6 yrs). We estimated this error to be 0.05 m.

Paleo RSL calculation

After relating all microatoll elevations to MSL, we used FMA and LMA elevation measurements to calculate paleo RSL. ~~To do so, w~~We then applied the concept of indicative meaning to coral microatolls. ~~(~~The indicative meaning allows to quantify the relationship between the RSL indicator and the former associated sea level (see Shennan, 1986 for definition and applications). To reconstruct paleo RSL from measured data we use the following formula ~~to coral microatolls 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 microatolls and **Er** is the estimated portion that was eroded from the upper fossil microatoll surface. In order to calculate RSL, we measured HLC at each island individually or at the closest neighboring island with living microatolls.

Concerning **HLC**, we surveyed living microatolls on Tambakulu (samples n=51) and Sanrobengi (n=24). On Suranti, 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.

The **Er** value was included in our calculation only in presence of visibly eroded microatolls (see Table 2~~Table 2~~ for details, field examples in Figure 2~~Figure 2~~) to account for lowering of microatolls due to erosion. In Figure 3~~Figure 3~~, related samples are indicated by light gray vertical error bars. ~~These elevations are less certain than elevations measured on non-eroded FMA and as we dated the top of all FMA, also the dated age (see Sampling and dating) is less certain due to the missing of the eroded carbon layers.~~ The mean thickness of living microatolls in the Spermonde Archipelago 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. We remark that this calculation does not take into account the fact that modern microatolls are thicker rather than wider because of the current rapidly rising sea level. In contrast, under Late Holocene falling or stable sea-level changes, they were presumably getting wider, but not thicker. Hence, in our calculations, the added **Er** might be overestimated, as it is based on modern microatoll proxies.

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

Final paleo RSL uncertainties were calculated using the root mean square of the sum of squares of the following values (see SM1 for calculations and details):

- Elevation errors of both FMA and LMA, calculated as described above

- Half of the indicative range, represented by the standard deviation of the measured heights of living corals, divided by two
- Uncertainty in estimating erosion = 0.19 m, derived from Mann et al. (2019) and discussed above.

Sampling and dating

~~Each Fossil microatolls~~ The highest point of each FMA was sampled by hammer and chisel, or with a hand drill. Sub-samples from all samples taken in the field 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.

After the XRD screening, we performed one radiocarbon dating per sampled microatoll. AMS radiocarbon dating and age calibration to calendar years before present (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 (the reservoir age of the ocean) 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.

The reason behind choosing a different delta R value than Mann et al. (2016) resides in the fact that the value they adopted (delta R = 89±70) was measured in southern Borneo (Southon et al., 2002) more than 900 km away from our study site. Their choice was based on the fact that 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), here we propose that there is no basis to assume a similar delta R value between southern Borneo and the Spermonde Archipelago. Therefore we follow the recommendation of Southon et al. (2002) to use a zero delta R, reported to be derived from unpublished data for the Makassar Strait.

All our samples were registered in the SESAR, the System for Earth Sample Registration, and assigned an International Geo-Sample Number (IGSN).

Glacial Isostatic Adjustment

In order to compare ~~RSL~~ observations with RSL caused by isostatic adjustment since the Last Glacial Maximum, ~~We~~ we calculated RSL as predicted by geophysical models of Glacial Isostatic Adjustment (GIA).~~,~~ ~~that~~ These 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. The latter are self-gravitating, rotating, radially stratified, deformable and characterized by a Maxwell viscoelastic rheology. We discretize the Earth's mantle in two layers: Upper and Lower Mantle (respectively, UM and LM). Each mantle viscosity profile is combined with a perfectly elastic lithosphere whose thickness is set to either 60, 90 or 120 km. We use 6 mantle viscosities for each lithospheric thickness, as shown in Table 1~~Table 1~~. We combine the Earth models with three different models: ICE5g, ICE6g (Peltier et al., 2015; Peltier, 2009) and ANICE (De Boer et al., 2015; De Boer et al., 2017). In total, we ran 54 different ice-earth model combinations (3 ice sheet models × 3 lithospheric thicknesses × 6 mantle viscosity profiles).

Table 1: Upper and lower mantle viscosities for the different Earth models.

Table 1

Results

Living and fossil microatolls

Our dataset consists of a total of 25 fossil microatolls (FMA) surveyed in five islands of the Spermonde Archipelago (Table 2~~Table 2~~, see also SM1). Sixeventeen microatolls yield ~~rounded average~~ ages (calendar years) ranging from 5970 a BP to 3615 a BP (Figure 3~~Figure 3~~a), while nine~~eight~~ yield ~~rounded~~ ages varying from 237 a BP to 37 a BP (Figure 3~~Figure 3~~b). These are added to the 20 fossil microatolls and one modern microatoll from Barrang Lompo and Panambungan previously reported by Mann et al. (2016) (Figure 3~~Figure 3~~a and Figure 3~~Figure 3~~c, see also SM1) and the data from De Klerk (1982) and Tjia et al. (1972) (Figure 3~~Figure 3~~c and Table 4~~Table 4~~, SM1). The microatoll PS_FMA 4 showed evidence of reworking, e.g., it was not fixed to the sea bottom, and thus it was subsequently rejected. Therefore, it is not shown in the results or discussed further.

Concerning living microatolls (LMA), our surveys included 51 individuals measured at the island of Tambakulu and 24 living microatolls measured at Sanrobengi (Figure 4~~Figure 4~~a). The living microatolls in this survey complement those measured by Mann et al. (2016) at Panambungan, Barrang Lompo and Sanane islands.

In order to reference the measured elevations to MSL as described in the methods section, we measured water levels at Barrang Lompo, Panambungan, Suranti, Tambakulu, Kodingareng Keke, Bone Batang and Sanrobengi for a total of 688 hours, over the period 6-Oct-2017 to 15-Oct-2017 (see water levels in SM1). An example of measured water levels is shown in Figure 4~~Figure 4~~b.

For which concerns XRD analyses (see SM1 for details), 17~~8~~ over 24 samples show an average value of aragonite at 98.7±1.1%. Among the other samples, one (SB_FMA26) contains 7% of calcite, which might affect its age. Other potential sources of secondary carbon might be present in PT_FMA9 and BB_FMA13 where Kutnohorite was detected ($CaMn^{2+}(CO3)^{2}$, respectively 3 and 6%). All the remaining samples show relatively low aragonitic content, but the other minerals contained in them does not contain carbon that could potentially affect the ages reported in this study.

The fossil microatolls of Suranti show age ranges from ~~114±114 a BP~~ 237±97 a BP to ~~237±97 a BP~~114±114 a BP. These samples indicate paleo RSL positions of -0.53±0.25 m and -0.11±0.25 m. On Tambakulu, ages range between ~~37±12 a BP~~114±114 a BP and ~~114±114 a BP~~37±12 a BP. In this time span, the elevations of the fossil microatolls at this island indicate RSL positions between -0.24±0.13 m and 0.11±0.23 m. The samples from Bone Batang cover ages from 5196±118 a BP to 3693±108 a BP and provide paleo RSL positions of 0.16±0.22 m to 0.23±0.22 m. Samples from fossil microatoll ages from Kodingareng Keke vary from 5869±99 a BP to 5343±88 a BP, indicating paleo RSL positions between 0.01±0.12 m and 0.13±0.12 m. Fossil microatoll samples from

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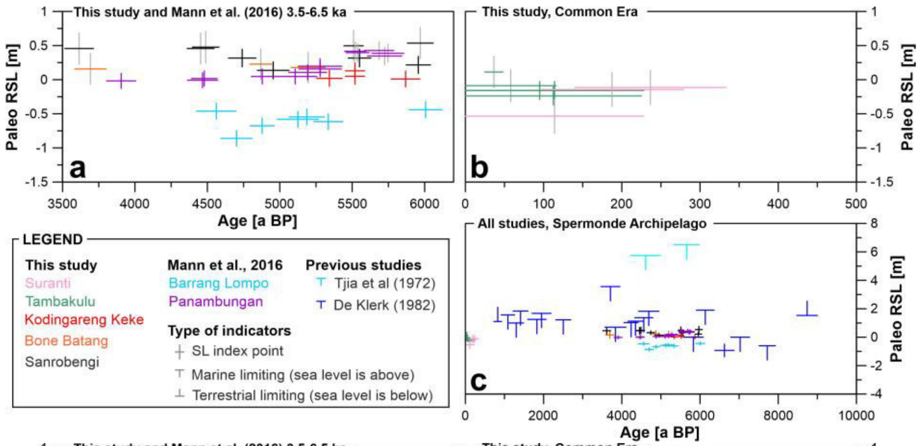
Sanrobengi range in age from 5970±89 a BP to 3615±99 a BP, with RSL from 0.14±0.12 m to 0.54±0.23 m.



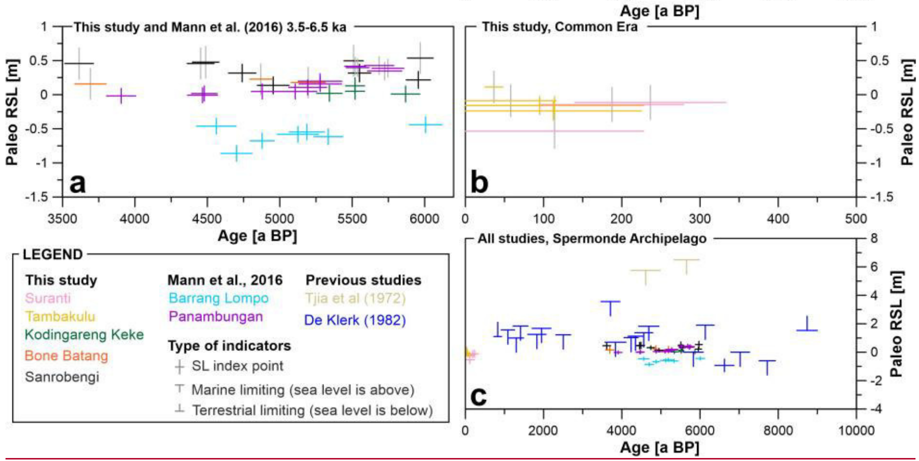


Figure 3: Representation of data reported in Table 2~~Table 2~~ and Table 3~~Table 3~~. a) RSL index points dating ~6 to ~3.5 ka and b) Common Era microatolls surveyed in this study. Gray vertical error bars in a) and b) represent the microatolls that were recognized as eroded in the field, and to which the erosion correction explained in the text has been applied. Panel c) shows the newly surveyed data in the context of previous studies.

Table 2: Fossil microatolls surveyed and dated at Suranti (PS_FMA 1 – 3), Tambakulu (PT_FMA 5 – 9), Bone Batang (BB_FMA 11 – 13), Kodingareng Keke (KK_FMA 14 – 17) and Sanrobengi (SB_FMA 18 – 26). All ages are recalculated with the delta R value of 0±0 (Southon et al., 2002). The elevation/age plot of these data is shown in Figure 3~~Figure 3~~a, b.

Table 2

Table 3: 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). The elevation/age plot of these data is shown in Figure 3~~Figure 3~~a.

Table 3

*Table 4: Marine and terrestrial limiting indicators from De Klerk (1982) and Tjia et al. (1972) studied in different locations in SW Sulawesi and the Spermonde Archipelago. This table is an extract from the database of Mann et al. (2019). * indicates samples from Tjia et al. (1972). The elevation/age plot of these data is shown in Figure 3~~Figure 3~~c.*

Table 4

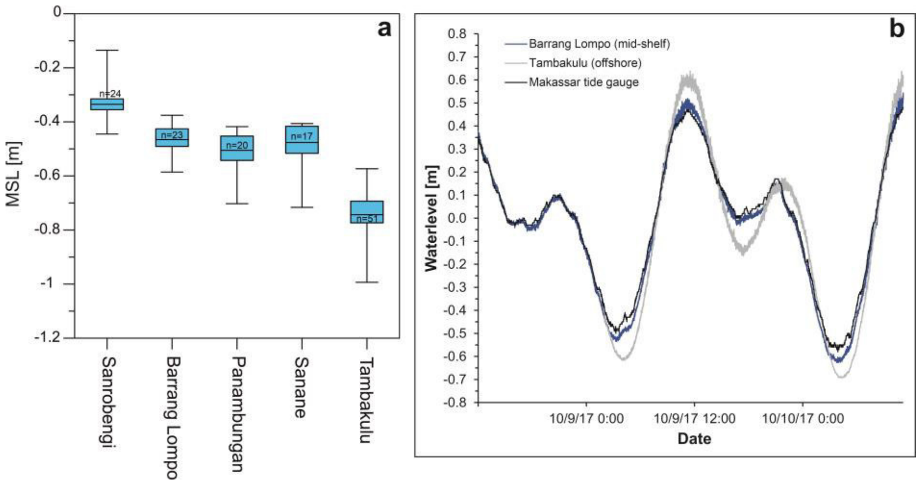
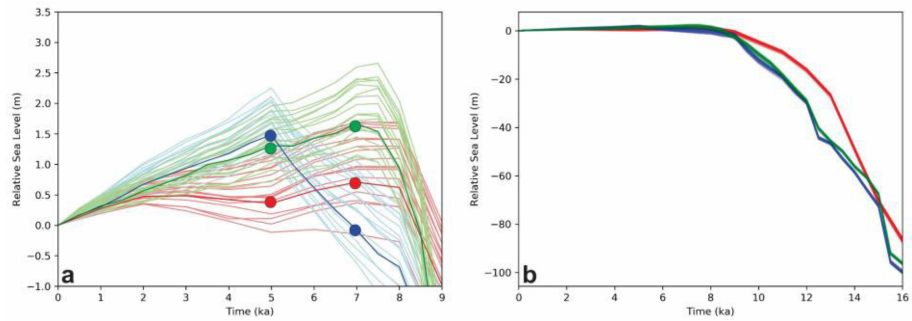


Figure 4: a) Box plot of the HLC elevations of individual microatolls measured in the Spermonde Archipelago; "n"= indicates how many individuals were surveyed on each island, the error bars show the highest and lowest LMA elevation. b) Comparison between water levels measured at Barrang Lompo (located on the mid-shelf), Tambakulu (located offshore towards the edge of the shelf) and data recorded by the national tide gauge at Makassar harbor. Note that, in a), 'zero' refers to mean sea level, while in b) 'zero' refers to the average water level over the measurement period (here 10/8/2017 to 10/10/2017).

GIA models

As described in the Methods section, we iterate different Earth and ice models to produce 54 different RSL predictions, from 16 ka BP to present (Figure 5~~Figure 5~~b). The models are available in the form of NetCDF files including longitudes between 55.3° to 168.9° and latitudes between -28.6° and 38.6°. We provide the models with a Jupyter notebook to extract data at a single location and plot GIA maps (files can be retrieved from SM2).

An extract of the modelling results is shown in Figure 5~~Figure 5~~ and Figure 6~~Figure 6~~. While all models predict a RSL highstand in the Spermonde Archipelago (Figure 5~~Figure 5~~a), the RSL histories predicted by each model show significant differences. ICE5g, in fact, predicts the RSL highstand occurring ca. 2.5 ka later than ANICE and ICE6g. The maximum RSL predicted by ICE5g and ICE6g is higher than the one predicted by ANICE. ANICE is the only ice model for which some Earth model iterations do not predict a RSL highstand, but a quasi-monotonous sea level rise from 8 ka BP to present.



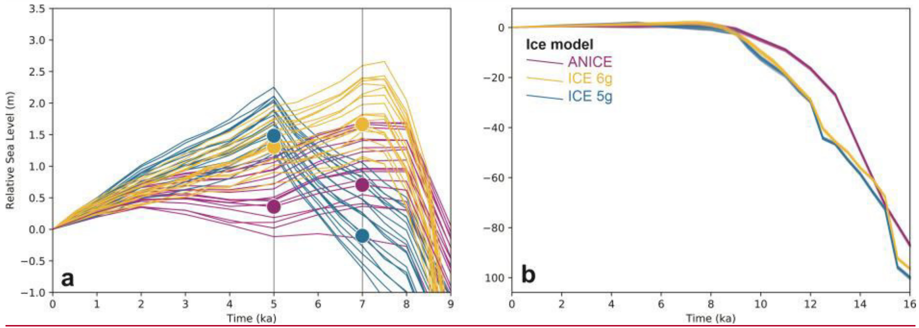


Figure 5: Results of the 54 GIA model runs for the Spermonde Archipelago, a) last 9 ka. Dots indicate the points at which the maps in Figure 6~~Figure 6~~ have been extracted. b) last 16 ka, representing the full time extent of the models. The eustatic sea level for each ice melting scenario is available in SM2. The Jupyter notebook used to create this graph is available as SM2.

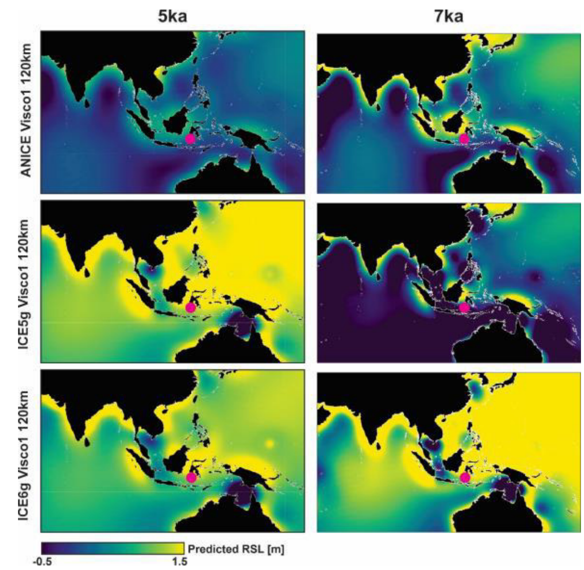


Figure 6: Relative sea level at 5 ka (left) and 7 ka (right) as predicted by three among the GIA models used in this study. See Table 1~~Table 1~~ for the definition of the mantle viscosity here labelled as "Visco1".

Discussion

The dataset presented in Table 2~~Table 2~~–4 and shown in Figure 3~~Figure 3~~a–c and Figure 4~~Figure 4~~ allow discussing several relevant points that need to be taken into account as Holocene sea-level studies in the Makassar Strait and SE Asia progress.

Measuring living microatolls for paleo RSL calculations

As indicated by former studies (e.g. Mann et al., 2016; Smithers and Woodroffe, 2001; Woodroffe et al., 2012) the best practice to calculate paleo RSL from microatolls is, when possible, to measure the height of living coral microatolls (HLC) below MSL, in order to calculate their indicative meaning (Meltzner and Woodroffe, 2015).

Our results (Figure 4~~Figure 4~~) show that, in the Spermonde Archipelago, HLC ~~changes substantially~~ is subject to changes over short spatial scales. In fact, within similar reef contexts, we measured significant differences in HLC across the Spermonde Archipelago, that seem to conform to a geographic trend directed from nearshore towards the islands located on the outer shelf. The highest HLC (closer to mean sea level) was measured at the island closest to the mainland (Sanrobengi). 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 and is, on average, ~0.4 m lower than that recorded at Sanrobengi. We highlight that this value is of the same magnitude (several decimeters) as the differences found by other studies reporting coral microatolls HLC measurements at different sites (Hallmann et al., 2018; Smithers and Woodroffe, 2001; Woodroffe, 2003; Woodroffe et al., 2012).

This pattern seems confirmed by the water level data we measured at the islands of Tambakulu and Barrang Lompo (Figure 4~~Figure 4~~b). While our measurements are too short in time to extract significant tidal datums, we remark that at Tambakulu (offshore) we measured a tidal range higher than at Barrang Lompo (mid-shelf), which in turn records a tidal range higher than the Makassar tide gauge (onshore). The local tidal range is related to the bathymetry and can therefore differ even in relatively close proximity. We highlight that, while a complete analysis of the water level data we surveyed is beyond the scope of this work, SM1 contains all the water levels recorded during our surveys for further analysis.

Our result stresses the importance of measuring the HLC of living microatolls also at very small spatial scales. In fact, had we only focused on the HLC published by Mann et al. (2016) for Panambungan, Sanane and Barrang Lompo (located in the center of the archipelago), our paleo RSL reconstructions would have been biased. Specifically, we would have overestimated paleo RSL at Tambakulu and underestimated it at Sanrobengi. Our reconstructions would have been similarly biased had we used for our paleo RSL reconstructions tidal datums derived from the tide gauge of Makassar.

Conflicting sea level histories

Additionally to our new dataset and that of Mann et al. (2016) presenting index points, there are two studies reporting paleo sea-level ~~data~~ observations for the Spermonde Archipelago: De Klerk (1982) and Tjia et al. (1972) (Figure 7~~Figure 7~~). Mann et al. (2019) re-analyzed data from these studies and recognized that most of the data originally interpreted as index points were instead better described as marine or terrestrial limiting indicators (Figure 3~~Figure 3~~c). Our new data agrees with those from Mann et al. (2016), but show relevant differences with Tjia et al. (1972) and De Klerk (1982) studies, that place RSL at 6–4 ka conspicuously higher than what is calculated using the microatoll record (Figure 3~~Figure 3~~c).

This mismatch was recently pointed out by Mann et al. (2019), who wrote: *"site-specific discrepancies between […] Tjia et al. (1972) […] and De Klerk (1982) and Mann et al. (2016) […] must be resolved with additional high-accuracy RSL data before the existing datasets can be used to decipher regional driving processes of Holocene RSL change within SE Asia"*.

While the study by Mann et al. (2016) was based only on two islands, the data presented in this study provide definitive evidence to call for a reconsideration of the data reported by Tjia et al. (1972) and De Klerk (1982). Notwithstanding the importance of these datasets, we highlight that the apparently higher late Holocene RSL histories reported by these two authors are largely at odds with precise RSL indicators such as coral microatolls. Hence, the question arises: what is the possible reason for Tjia et al. (1972) and De Klerk (1982) data to be higher than the data reported by this study and Mann et al. (2016)?

One possible source of mismatch could reside in regional GIA differences. We suggest ~~to~~ rejecting this hypothesis comparing the location of the areas surveyed in the Spermonde Archipelago with the outputs of our GIA models. Using the GIA models producing the most extreme differences within our region, we show that the discrepancy between the data cannot be explained by regional differences in the GIA signal. In fact, GIA differences remain within one meter among our sites (Figure 7~~Figure 7~~a, b).

Similarly to GIA, another possible hypothesis is that the differences among sites in the Spermonde Archipelago are caused by differential tectonic histories between sites. While this is a possibility that would need further paleo RSL data to be explored (expanding the search of RSL indicators beyond the islands of the Spermonde Archipelago), we argue that there are several inconsistencies between the microatoll data and other sea-level data points surveyed within short geographic distances. For example, a ~~n unspecified~~ fossil coral (not specified if in growth position) surveyed at Tanah Keke (GrN-9883, Table 4~~Table 4~~) by De Klerk (1982) would indicate that, at 4237±180 a BP, RSL was above 1.03~~25~~ m. At the same time, microatoll data from Sanrobengi (SB_FMA25, Table 2~~Table 2~~, ~20 km North of Tanah Keke) show that RSL was 0.46±0.23m above present sea level. Similarly, at the site of Sarappo, De Klerk (1982) surveyed coral and shell accumulations that would propose the sea level was above 0.7 m at 3837±267 a BP (GrN-10978). This data point is at odds with microatoll data from the nearby islands of Panambungan, Bone Batang and Sanrobengi where, at the same time RSL is recorded by microatolls at elevations between -0.02±0.11 m and 0.46±0.23 m (BB_FMA13, SB_FMA26, Table 2~~Table 2~~ and FMA14 (PP), Table 3~~Table 3~~). We argue that invoking significant differential tectonic shifts between islands located so closely in space would require the presence of tectonic structures on the shelf of the Spermonde Archipelago that are, at present, unknown.

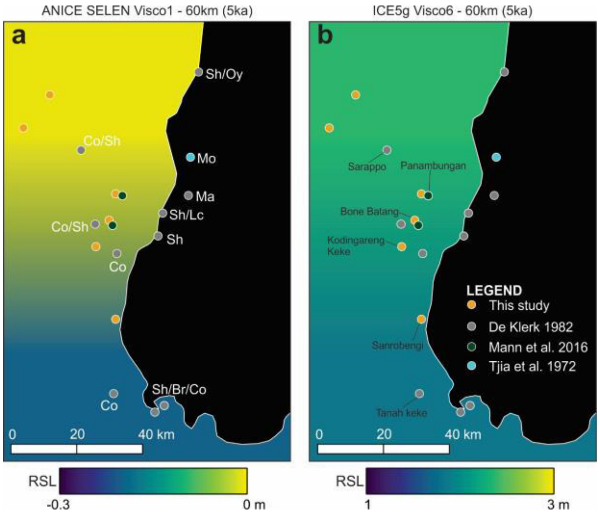


*Figure 7: Location of the RSL data presented in this study, Mann et al. (2016), De Klerk (1982) and Tjia et al. (1972) compared with RSL as predicted by GIA models. Here we show the models predicting, respectively, the lowest (a) and highest (b) RSL in the Spermonde Archipelago. Labels in a) represent the type of indicator reported by De Klerk (1982) and Tjia et al. (1972). Island names in b) refer to the islands mentioned in the discussion. Legend: **Sh** – shell accumulations; **Oy** – Oysters (no further details available); **Mo** – mollusks fixed on Eocene bedrock; **Ma** – Peat from Maros; **Lc** – Loamy clays; **Br** – Beachrock; **Co** – Corals (in situ?). In b) we report the names of the islands discussed in the main text.*

Another possibility is that, while the original descriptions of Tjia et al. (1972) and De Klerk (1982) seem to indicate "marine limiting" points (Mann et al., 2019), some of them may be instead representative of other environments. For example, it is not clear whether the "shell accumulations" reported at several sites and interpreted by Mann et al. (2019) as marine limiting points may be instead representative of high-magnitude wave deposits by storms. The Spermonde Archipelago is subject to occasional strong storms that may explain the high emplacement of these deposits (see wave statistics in Figure 8~~Figure 8~~).

Also tsunamis are not unusual along the coasts of SE Asia (e.g. Rhodes et al., 2011) with the broader region in the Makassar Strait being one of the most tsunamigenic regions in Indonesia (Harris and Major, 2017; Prasetya et al., 2001). Nevertheless, the tsunamigenic earthquakes reported in this region are far north with respect to our study area (Prasetya et al., 2001, see left panel in Figure 8~~Figure 8~~), and in general they are shallow and too small in magnitude to produce significant tsunamis propagating towards the Spermonde Archipelago. The earthquakes in this area are all generated along the Paternoster transform fault, which would point to tsunamis generated mostly by earthquake-triggered landslides rather than earthquakes themselves. Nevertheless, a tsunamigenic source for marine sediment deposition significantly above MSL cannot be ruled out until the deposits reported by Tjia et al. (1972) and De Klerk (1982) are re-investigated with respect to their precise elevations above MSL and their sediment facies.

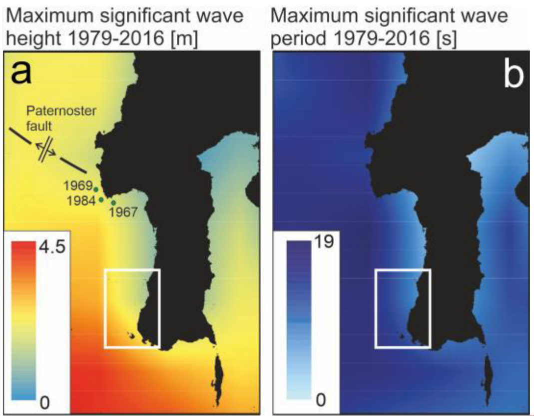


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Figure 8: Maximum significant wave height (a) and period (b) extracted from the CAWCR wave hindcast (Durrant et al., 2013; Durrant et al., 2015~~; Durrant et al., 2015~~). The left panel shows the approximate location and year of the three historical tsunami records reported by Prasetya et al. (2001), their Figure 1. Faultline and axis of spreading of the Paternoster fault are derived from Prasetya et al. (2001), their Figure 5. The box delimited by the white line indicates the approximate location of Figure 7~~Figure 7~~ within this figure. CAWCR source: Bureau of Meteorology and CSIRO Copyright 2013.

Mismatch of the record of Barrang Lompo Island

As shown in Figure 3~~Figure 3~~a, the data presented in this study together with the data from Mann et al. (2016), confirm a sea level history with a higher-than-present RSL at 6–3.5 ka BP. The only exception to this pattern is the island of Barrang Lompo, where microatolls of roughly the same age are consistently lower (light blue crosses in Figure 3~~Figure 3~~a). We compare the data at Barrang Lompo to the other RSL data points in the Spermonde Archipelago using a Monte-Carlo simulation (see SM2 for details and methods) to highlight spatio-temporal clustering in these two datasets. We calculate that, on average, at ~5100 a BP, RSL at Barrang Lompo is 0.8±0.3 m lower than all the other islands where we surveyed microatolls of the same age (Figure 9~~Figure 9~~).

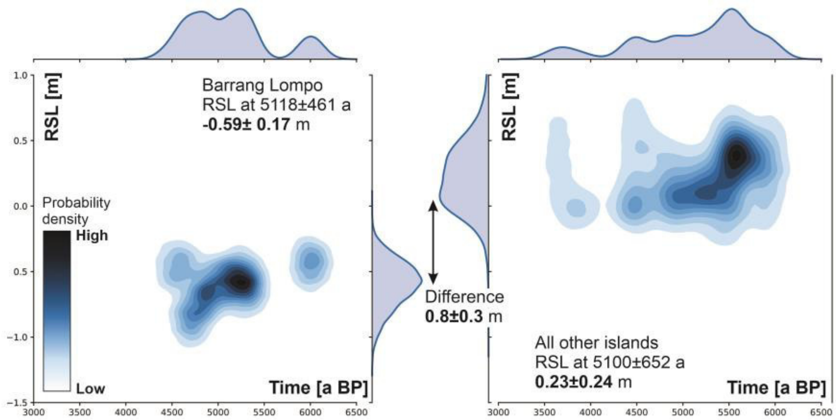


Figure 9: Jointplot showing bivariate (central plot) and univariate (marginal axes) distribution of RSL data points at Barrang Lompo (left) and all the other islands surveyed in this study and in Mann et al. (2016) (right). Darker blue areas in the central plots indicate a higher density of RSL point therefore darker colors indicate a higher probability of RSL at the given time. The Jupyter notebook used to create this graph is available as SM2.

The mismatch in RSL histories described above can hardly be reconciled by differential crustal movements due to either tectonics or GIA over such short spatial scales (Figure 1~~Figure 1~~b). For example, Bone Batang (where fossil microatolls were surveyed slightly above present sea level) and Barrang Lompo (where microatolls of roughly the same age were surveyed 0.8 m below those of Bone Batang) are separated by less than 5 km and is, hence, highly unlikely that they were subject to very different tectonic or isostatic histories.

The only geographic characteristic that separates Barrang Lompo from the other islands we surveyed is that it is heavily populated (~4.5 thousand people living on an island of 0.26 km²) (Syamsir et al., 2019). As such, it is characterized by a very dense network of buildings and concrete docks. The island is also subject to groundwater extraction (at least 8 wells were reported on Barrang Lompo, Syamsir et al., 2019).

The island of Barrang Lompo was populated since at least the 1720s (Clark, 2010; de Radermacher, 1786 as cited in Schwerdtner Manez and Ferse, 2010) when Barrang Lompo was (as it is today) a hub for sea cucumber fisheries (Schwerdtner Manez and Ferse, 2010). Assuming that the localized subsidence is anthropogenic, we cannot exclude that it started since the early colonization, but it seems appropriate to date it back to, at least 100–150 years ago, since the island population started to grow and to extract more groundwater for its own sustenance. Using these inferences, Barrang Lompo might be affected by a subsidence rate in the order of ~3–11 mm/a (depending on the adopted subsidence amount and time of colonization) compared to the non-populated islands in the archipelago. ~~We note that, while relatively high,~~Notwithstanding the obvious differences in patterns and causes of subsidence, we note that ~~-~~this rate is at least one order of magnitude smaller than ~~the subsidence rates~~ what is observed in Indonesian mega-cities due to anthropogenic influences (Alimuddin et al., 2013). As this subsidence rate is a relative rate among different islands, any other natural subsidence or uplift rate (i.e., tectonic uplift or GIA-induced vertical land motions) should be added to this estimate.

As the fossil microatolls surveyed at anomalous positions were all located near the coast, we propose that they might have been affected by local subsidence due to the combined effect of groundwater extraction and construction load on the coral island. One point worth highlighting is that the depth of living microatolls, surveyed on the modern reef flat few hundred meters away from the island, does not show significant differences when compared to other islands nearby (Figure 4~~Figure 4~~). If the island is indeed subsiding, this observation could be interpreted in two ways. One is that the subsidence might be limited to the portions closer to the shoreline, and not to the distal parts (i.e., the reef flat) where modern microatolls are growing. The second is that the island has been subsiding fast in the recent past, but is now subsiding at roughly the same rate of upward growth of the living microatolls (Simons et al., 2007). Meltzner and Woodroffe (2015) report that microatolls are in general characterized by growth rates of ~10 mm/a, with extremes between 5 to 25 mm/a for those belonging to the genus *Porites*.

A partial confirmation of a possible subsidence pattern at Barrang Lompo is given by the intense erosion problems that this island is experiencing, which may be the consequence of high rates of land subsidence. Relatively recent reports indicate that coastal erosion is a particularly striking problem at Barrang Lompo (Williams, 2013; Tahir et al., 2012). Interviews of the local community led by Tahir et al. (2009) indicate that large parts of the island suffer from severe erosion problems, and that "*coastline retreat has occurred with a rate of change of 0.5 m/yr*". Williams (2013) reported that "*local people had constructed a double seawall of dead coral to mitigate erosion*".

We recognize that the mechanism of subsidence for Barrang Lompo proposed above should be regarded as merely hypothetical and needs confirmation by means of independent datasets. For example, the RSL change rates we propose for Barrang Lompo would be observable by instrumental means. For example, a comparative study using GPS measurements for a few days per year over a period of 3–5 years would provide enough information to inform on vertical land motion rates in Barrang Lompo. Another approach would be the use of tide gauges to investigate multi-yearly patterns of land and sea-level changes in Barrang Lompo. Compared to other nearby islands, it would surely help understanding the reasons for the mismatch highlighted by our data. To our knowledge, there is only one instrumental example of the kind of subsidence we infer here. At Funafuti Island (Tuvalu), Church et al. (2006) report that two closely located tide gauges (ca. 3 km apart) show a difference of RSL rise rates. They state that "*this tilting may be caused by tectonic movement or (most probably) local subsidence (for example, due to groundwater withdrawal) and demonstrates that even on a single island, the relative sea-level trend may differ by as much as 0.6 mm yr^{-1}*".

Another way to detect recent vertical land movements between the island of Barrang Lompo and other uninhabited islands nearby would be to investigate whether there are differences in the morphology and growth patterns of living microatolls. In fact, if Barrang Lompo rapid subsidence is affecting also the distal part of the reef, this may be detectable through higher annual growth rates of the microatolls at this island with respect to that affecting other islands.

Common Era microatolls

Eight microatolls from the islands of Suranti and Tambakulu (located in the North of our study area, 12 km apart from each other) yielded ages spanning the last ~300 years (Figure 3~~Figure 3~~b). This period of time represents the most recent part of the Common Era. Sea-level data from this period are relevant to assess rates of sea-level changes beyond the instrumental record (Kopp et al., 2016). Within Southeast Asia, the database of Mann et al. (2019) (DOI: 10.17632/mr247yy42x.1 - Version 1) reports only one index point for this time frame (Singapore, Bird et al., 2010).

As the two islands of Suranti and Tambakulu are uninhabited and hence are not subject to the hypothetical anthropogenic subsidence discussed above for the island of Barrang Lompo, it is possible to use these data to calculate short-term vertical land motions. To do this, we first need to correct the paleo RSL as reported in Figure 3~~Figure 3~~b to account for 20th century sea-level rise and GIA land uplift since the microatolls were drowned (see SM2 for the complete calculation). We make this correction using the 20th century global sea-level rise of 184.8±25.9 mm (Dangendorf et al., 2019) and GIA rates from our models (0.36±0.09 mm/a, see SM1 for details). We remark that this correction applied to our data represents an approximation, as we use global 20th century RSL rise rates instead of local rates, which are not available for this area due to the absence of a long-term tide gauge. Yet, it can give an insight on potential land motions in the Spermonde Archipelago.

We then iterate multiple linear fits through our data points by randomly selecting ages and CE RSL corrected as described above (full procedure and script available in SM2). After 10^4 iterations, we calculate that the average VLM rate indicated by our microatolls is -0.88±0.61 mm/a (Figure 10~~Figure 10~~). While this range indicates that natural subsidence might be occurring at these islands we cannot discard the possibility of a slight uplift or stability.

While caution is needed when comparing long-term rates to the short-term ones measured by GNS~~P~~S stations, ~~We~~ we remark that ~~this value~~ the values we calculate are ~~is~~ in agreement with the average vertical motion of -0.92±0.53 mm/a reported by Simons et al. (2007) (see their Supplementary Table 6) for the *PARE* GPS station (Lon: 119.650°, Lat: -3.978°, Height: 135 m). This station is~~,~~ located on the mainland, 78 km ENE of Tambakulu and Suranti. Nevertheless, the subsidence indicated by both our data and the *PARE* station appear at odds with another GPS station reported by Simons et al. (2007) in the proximity of Makassar (*UJPD,* Lon: 119.581°, Lat: -5.154°, Height: 153 m), that measures instead uplift rates at rates of 2.78±0.60 mm/a.

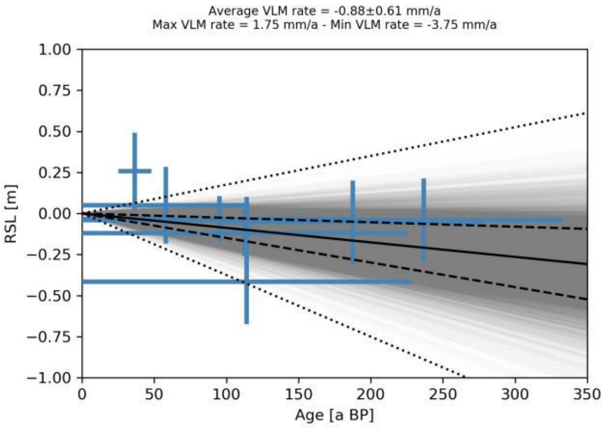


Figure 10: Common Era data points, corrected for 20th century sea-level rise and GIA uplift (blue crosses). Gray lines show the results of re-iterating a linear fit through random normal samples of the blue points. Dotted black lines show the linear fits with maximum and minimum slopes. Dashed black lines show average + standard deviation and average – standard deviation slopes. The solid black line shows the average slope. The Jupyter notebook used to create this graph is available as SM2.

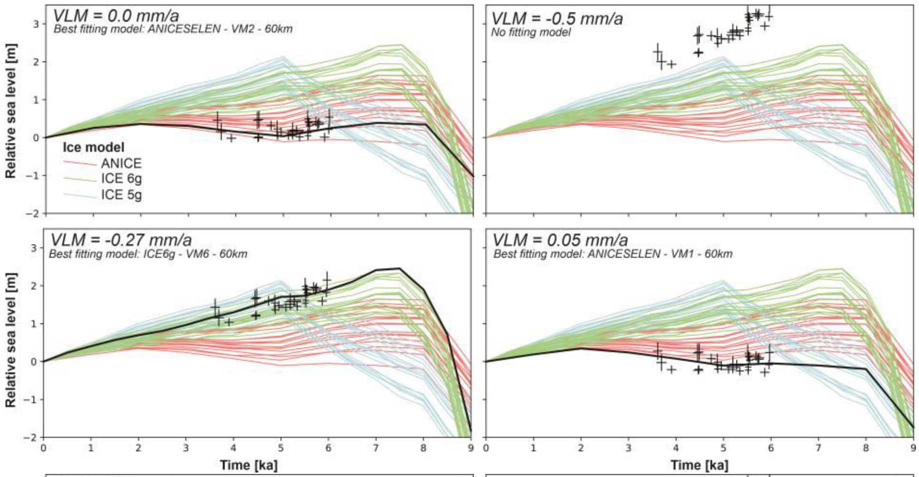
Comparison with GIA models

Excluding the microatoll data from the island of Barrang Lompo (that, as per discussion above, may have been subject to recent subsidence), 298 fossil microatolls in the Spermonde Archipelago (including also the data reported by Mann et al., 2016, Figure 3Figure 3a) date between 3615 to 5970 a BP. This dataset can be compared with the predicted RSL from GIA models once vertical land movements due to causes different from GIA are taken into account considered. To estimate such movements in the Spermonde Archipelago, two options are available.

The first is to consider that the area has been tectonically stable during the Middle Holocene. This is plausible under the notion that, unlike the northern sector of Western Sulawesi (that is characterized by active lateral and thrust faults, (Bird, 2003), South Sulawesi is not characterized by strong tectonic movements (Sasajima et al., 1980; Hall, 1997; Walpersdorf et al., 1998; Prasetya et al., 2001). Considering the Spermonde Archipelago as tectonically stable (Figure 11Figure 11a), our RSL data show a best fit with the RSL predicted by the ANICE model (VM2 – 60km, see Table 1Table 1 for details), in particular with those iterations predicting RSL at 6–4 ka few decimeters higher than present.

The second option is to interpret the rate of RSL change calculated from Common Era fossil microatolls (-0.88±0.61 mm/a), and make two assumptions: 1) that they were uniform through time and 2) that they can be applied to the entire Archipelago. Under these assumptions, we show in Figure 11Figure 11b that, with subsidence rates below -0.5 mm/a, our data do not match any of our RSL predictions. Data start to match RSL predictions obtained using the ICE6g ice model with lower subsidence rates. For example, with a subsidence rate of -0.27 mm/a, representing the upper end of the 2-sigma range shown in Figure 10Figure 10), the data show a good match with ICE6g (Figure 11Figure 11c). As discussed above, based on both our Common Era data and GPS data from Simons et al. (2007) we cannot exclude that, instead of subsidence, the Archipelago is characterized by tectonic uplift. The maximum uplift compatible with our RSL data and models is 0.05 mm/a (Figure 11Figure 11d).

Regardless of the tectonic history chosen, we note that our data does not match the peak highstand predicted at 5 ka by the iterations of the ICE5g model.



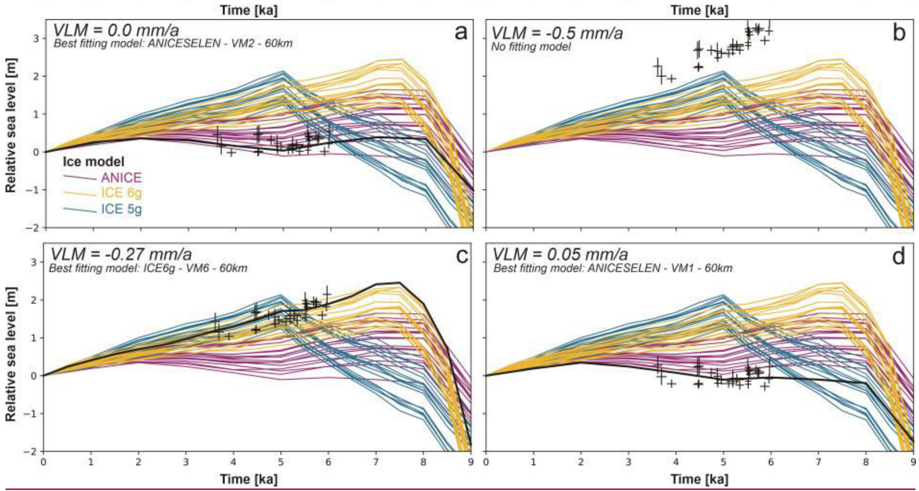


Figure 11: Comparison between RSL observations and predictions from GIA models (see Table 1~~Table 1~~ for model details). Red, green and blue lines represent, respectively, ANICE, ICE5g and ICE6g models. Black lines identify best fitting models. The different panels (a-d) show different tectonic corrections applied to the observed RSL data. The Jupyter notebook used to create this graph is available as SM2.

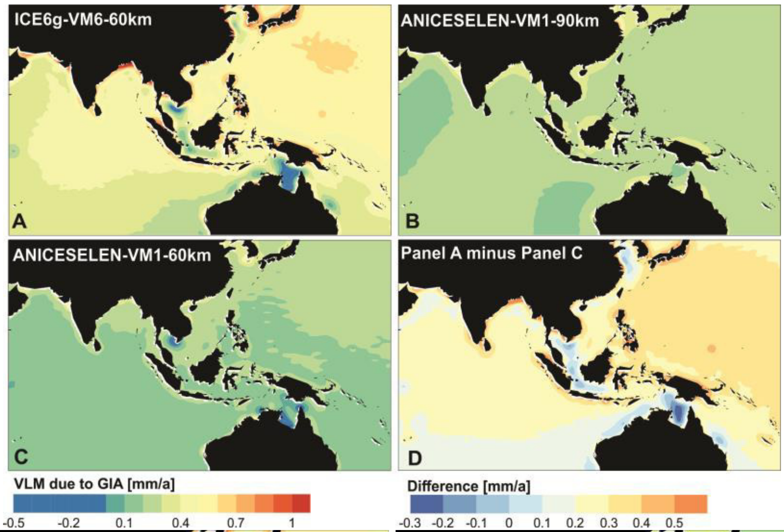
Paleo to modern RSL changes

The different possible~~best~~ matches between paleo RSL data and GIA models shown in Figure 11~~Figure 11~~ have a broader significance concerning rates and patterns of modern changes in relative sea level at broad scale. In fact, GIA effects need to be taken into account in the analysis of both tide gauge and satellite altimetry data (see Rovere et al., 2016 for a review). One way to choose the GIA model(s) employed for this correction is to select those matching better with Late Holocene data.

To make an example of how different modelling choices propagate onto modern RSL estimates, in Figure 12~~Figure 12~~a–c, we show the modern rates of ~~GIA VLM predicted~~ GIA predicted by three models across Southern and Southeast Asia matching different assumptions on VLM (as shown in Figure 11).

~~by the three different models highlighted in Figure 11 as best matching with our data under different vertical land motion assumptions.~~ The difference between the two most extreme models matching with our data is within -0.3 and ~~-~~0.5 mm/a (Figure 12~~Figure 12~~d), and it appears widely relevant ~~also~~ within the broader geographic context included in our models.

For example, the values shown in Figure 12d show that ICE6g-VM6-60km predicts faster modern GIA rates than ANICESELEN-VM1-60km for India and Sri Lanka. As these rates would need to be subtracted from the data recorded by a tide gauge, this would have an effect on any attempt of decoupling the magnitude of eustatic vs other land motions at ~~that~~ tide gauges in that area.



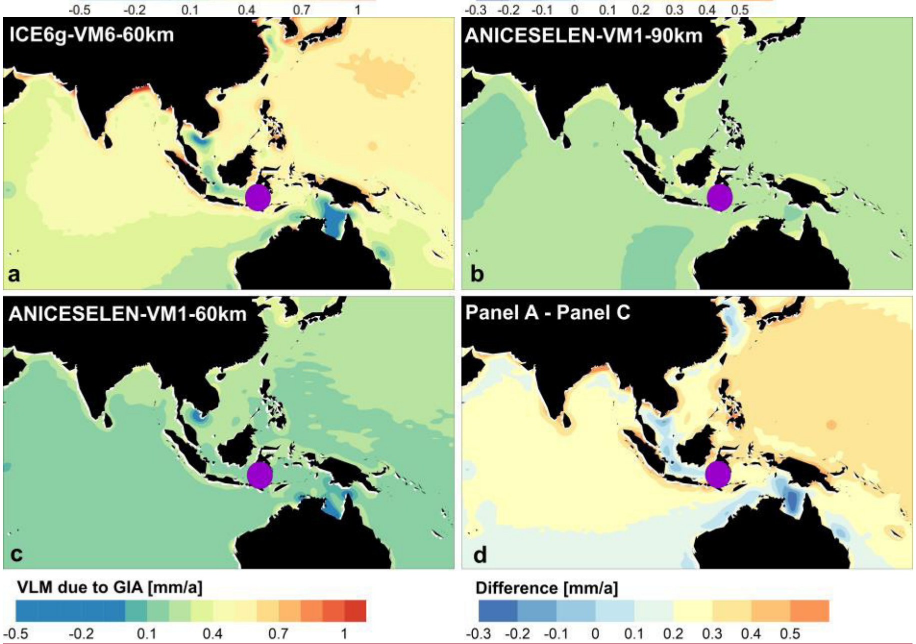


Figure 12 a-c) GIA-induced vertical land motion derived by linearly interpolating the last time step in our models (1 ka for ANICE, 0.5 ka for ICE6g) to present. d) Difference between the models with the most extreme predictions matching our Late Holocene sea level index points under different vertical land motion scenarios (see Figure 11Figure 11).

Conclusions

In this study, we report 25 new RSL index points (of whichwhile one index point was rejected due to evidences of reworking) and 75 living microatoll measurements from the Spermonde Archipelago. We also report 54 new GIA model iterations that span a large geographic region extending beyond Southeast Asia. Together with the data reported in Mann et al. (2016) these represent an accurate dataset against which paleo RSL changes in the Spermonde Archipelago and adjacent coasts (including the city of Makassar, the seventh largest in Indonesia) can be benchmarked. There are multiple implications deriving from our discussions that we summarize below.

Our measurements of living microatolls show that there is a gradient from the nearshore islands of the Archipelago towards the outer shelf ones. The magnitude of this gradient seems to be confirmed by water level data we measured at different islands and is ca. 0.4 m, with living microatolls deepening towards the offshore area. Recognizing the presence of this gradient was important in order to obtain coherent RSL reconstructions among different islands. This strengthens the notion that, when using microatolls as RSL indicators, living microatolls must be surveyed in close proximity of fossil ones in order to avoid biases in sea level reconstructions.

The data surveyed in the Spermonde Archipelago by De Klerk (1982) and Tjia et al. (1972) are largely at odds with precisely measured and interpreted fossil microatolls presented in this study. We propose that, pending more accurate elevation measurements and new interpretation of these data, they are excluded from sea-level compilations (i.e., Mann et al., 2019 in Khan et al., 2019). We propose that there is the possibility that these deposits might represent storm (or tsunami) accumulations: this hypothesis needs further field investigations to be tested.

Data from the heavily populated island of Barrang Lompo are significantly lower (ca. 80 cm) than those at all the other islands. Here, we propose the hypothesis that groundwater extraction and loading of buildings on the island may be the cause of this discrepancy, that would result in local subsidence rates of Barrang Lompo in the order of ~3-11 mm/a. Due to the lack of instrumental data to support our hypothesis, we highlight the need of future studies acquiring both instrumental records and high-resolution RSL histories from fossil microatolls (e.g., reconstructing die-downs from microatoll slabs) across islands with different human population patterns. If verified, this mechanism of local subsidence would have wider implications for the resilience of low-lying, populated tropical islands to changes in sea level.

Besides the mechanism of local anthropogenic subsidence, we propose for the island of Barrang Lompo, eight microatolls dating to the last ca. 300–400 years give us the opportunity to calculate recent vertical land motion rates. Using different subsets of these data, we calculate that they may indicate average subsidence rates of 0.88±0.61 mm/a. As these rates were calculated only for the two offshore islands in our dataset, we advise caution in extrapolating to broader areas. Nevertheless, we point out that this rate of subsidence is very consistent with that derived from a GPS station less than 100 km away (that recorded a rate of -0.92±0.53 mm/a, Simons et al., 2007), but at odds with another GPS station in Makassar, for which uplift is reported.

Comparing the part of our dataset dated to 3–4 ka with the RSL predictions from a large set of GIA models, we show that the best matching ice model depends on the assumptions on vertical land movements. A generally better fit with models using the ICE6g ice history is obtained with moderate subsidence rates (-0.27 mm/a), while models using the ANICE ice history are more consistent with hypotheses of stability or slight tectonic uplift (0.05 mm/a). The ice model ICE5g shows a peak in RSL at ca. 5 ka that does not match with our RSL observations at the same time.

In this study, we are~~do~~ not favoring one model over the others nor claim~~.~~ ~~We also do not claim~~ that our model ensemble is a complete representation of the possible variable space. We use the example of the Spermonde Archipelago to highlight how ~~Our take-home message is that GIA modeling choices, informed by~~ Holocene RSL data, coupled with GIA models, can inform ~~have an obvious effect~~ on two aspects that are ultimately of interest for coastal populations. First, they may help defining local subsidence rates beyond modern technologies. It appears that, for the Spermonde Archipelago, long-term subsidence, tectonic stability or slight uplift are all possible. To settle this uncertainty, instrumental measures and more precise Ccommon Eera sea level datasets should represent a focus of future sea-level research in this area. Second, we showed here that matching GIA model predictions with Late-Holocene RSL data areis useful to constrain which models might be a better choice to predict ongoing regional rates of GIA. While we do not have a definite “best match” for the Spermonde Archipelago, we suggest that iterations of ICE6g and ANICESELEN fit better with our data, and might produce more reliable GIA predictions than ICE5g, that seems not to match as well as the other two.

~~As a final remark, we highlight that GIA needs to be accounted for to correct tide gauge data and derive current rates of eustatic sea-level changes. Under this perspective, disentangling which combination of Earth and ice models produces best-fitting RSL histories with late Holocene data is central in order to improve our understanding of future sea-level changes.~~ In order to enable data/model comparisons such as the one performed in this study the supplementary material (SM2) contains all our model results at broad spatial scales for Southern and Southeast Asia.

Author contributions

MB organized fieldwork and sampling, which were conducted in collaboration with TM and DK. JJ gave on-site support in Makassar and provided essential support with sampling and research permits in Indonesia. MB organized the data analysis, with supervision and inputs by TM and AR. The python codes provided in the Supplementary material were written by AR. TS and JI analyzed the tidal datum and calculated MSL, providing expertise on modern sea-level processes. PS offered expertise, performed model runs and provided discussion inputs on Glacial Isostatic Adjustment. MB drafted the first version of the manuscript. MB and AR wrote the final version of the manuscript jointly. All authors revised and approved the content of the manuscript.

Declaration of Interest

The authors declare no conflict of interest

Data availability

SM1 – spreadsheet including 10 sheets containing the following information.

Sheet 1 – Site coordinates: Coordinates of the islands surveyed in this study and in Mann et al., 2016. The sheet includes the tidal model outputs calculated for each island and statistics on tidal levels.

Sheet 2 – Water level logger: raw data of the water level loggers positioned at each island, including date/time, depth and coordinates of deployment.

Sheet 3 – MSL calculations: details of the calculations done to reduce the water level at each island to MSL.

Sheet 4 – Complete table: spreadsheet version of the Tables 2, 3, 4 in the main text.

Sheets 5-9 – Data for each island: details on living and fossil microatolls surveyed at each island.

Sheet 10 – Modern GIA: current GIA rates for the Spermonde Archipelago extracted from the last time step of ANICE (1ka), ICE5g and ICE6g (0.5ka).

Sheet 11 – Results of XRD elemental analysis.

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SM2 – NetCDF files of GIA models and collection of Jupyter notebooks to reproduce the analyses in the paper. Available here: http://doi.org/10.5281/zenodo.3597352

SM3 – Laboratory data for Radiocarbon analyses.

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Table 2: Fossil microatolls surveyed and dated at Suranti (PS_FMA 1 – 3), Tambakulu (PT_FMA 5 – 9), Bone Batang (BB_FMA 11 – 13), Kodingareng Keke (KK_FMA 14 – 17) and Sanrobengi (SB_FMA 18 – 26). All ages are recalculated with the delta R value of 0±0 (Southon et al., 2002). The elevation/age plot of these data is shown in Figure 3a, b.

IGSN	Lab Code	Sample Name	Island Name	14 C age	± 14 C error	Mean age [cal a BP]	± Error (yr)	Elevation [m] with respect to msl	HLC [m]	RSL [m]	± Vertical error [m]	+ Erosion error (σEr) [m]
IEMBMPSFMA1	Beta – 487554	PS_FMA1	Suranti	490	30	114	114	-1.46	-0.72-0.74	-0.53	0.25	0.2
IEMBMPSFMA2	Beta – 508373	PS_FMA2	Suranti	560	30	187.5	91.5	-1.20	-0.72-0.74	-0.14	0.25	0.33
IEMBMPSFMA3	Beta – 487555	PS_FMA3	Suranti	620	30	236.5	96.5	-1.17	-0.72-0.74	-0.11	0.25	0.33
IEMBMPTFMA5	Beta – 487558	PT_FMA5	Tambakulu	460	30	95	95	-0.88	-0.72-0.74	-0.16	0.13	0
IEMBMPTFMA6	Beta – 508375	PT_FMA6	Tambakulu	490	30	114	114	-0.88	-0.72-0.74	-0.16	0.13	0
IEMBMPTFMA7	Beta – 508376	PT_FMA7	Tambakulu	470	30	112.5	112.5	-0.96	-0.72-0.74	-0.24	0.13	0
IEMBMPTFMA8	Beta – 487559	PT_FMA8	Tambakulu	106.55	0.4 pMC	36.5	11.5	-0.81	-0.72-0.74	0.11	0.23	0.2
IEMBMPTFMA9	Beta – 508377	PT_FMA9	Tambakulu	420	30	58	58	-0.94	-0.72-0.74	-0.09	0.23	0.13
IEMBMBBFMA11	Beta – 487545	BB_FMA11	Bone Batang	4630	30	4869	75	-0.56	-0.50	0.23	0.22	0.28

IEMBMBBFMA12	Beta – 487546	BB_FMA12	Bone Batang	4910	30	5196	118	-0.63	-0.50	0.18	0.22	0.3
IEMBMBBFMA13	Beta – 508378	BB_FMA13	Bone Batang	3750	30	3692.5	107.5	-0.65	-0.50	0.16	0.22	0.3
IEMBMKKFMA14	Beta – 487556	KK_FMA14	Kodingareng Keke	4970	30	5342.5	87.5	-0.45	-0.47	0.02	0.12	0
IEMBMKKFMA15	Beta – 508379	KK_FMA15	Kodingareng Keke	5500	30	5868.5	98.5	-0.46	-0.47	0.01	0.12	0
IEMBMKKFMA16	Beta – 487557	KK_FMA16	Kodingareng Keke	5160	30	5519.5	65.5	-0.34	-0.47	0.13	0.12	0
IEMBMKKFMA17	Beta – 508380	KK_FMA17	Kodingareng Keke	5160	30	5519.5	65.5	-0.42	-0.47	0.05	0.12	0
IEMBMSBFMA18	Beta – 487547	SB_FMA18	Sanrobengi	4730	30	4954.5	109.5	-0.17	-0.31-0.33	0.14	0.12	0
IEMBMSBFMA19	Beta – 508371	SB_FMA19	Sanrobengi	5560	30	5956.5	83.5	-0.09	-0.31-0.33	0.22	0.12	0
IEMBMSBFMA20	Beta – 487548	SB_FMA20	Sanrobengi	5140	30	5509.5	66.5	-0.14	-0.31-0.33	0.50	0.23	0.33
IEMBMSBFMA21	Beta – 487549	SB_FMA21	Sanrobengi	5570	30	5970	89	-0.10	-0.31-0.33	0.54	0.23	0.33
IEMBMSBFMA22	Beta – 487550	SB_FMA22	Sanrobengi	5200	30	5550.5	77.5	0.01	-0.31-0.33	0.32	0.13	0
IEMBMSBFMA23	Beta – 487551	SB_FMA23	Sanrobengi	4550	30	4740.5	94.5	0.01	-0.31-0.33	0.32	0.13	0
IEMBMSBFMA24	Beta – 487552	SB_FMA24	Sanrobengi	4350	30	4488.5	91.5	0.02	-0.31-0.33	0.48	0.23	0.15

IEMBMSBFMA25	Beta – 487553	SB_FMA25	Sanrobengi	4320	30	4453.5	92.5	0.00	-0.31-0.33	0.46	0.23	0.15
IEMBMSBFMA26	Beta – 508372	SB_FMA26	Sanrobengi	3700	30	3614.5	98.5	0.00	-0.31-0.33	0.46	0.23	0.15