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Nerilie Abram,
Editor
Climate of the Past

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Response to reviewer comments for the manuscript titled 'A sub-fossil coral Sr/Ca record documents meridional variability of the Intertropical Convergence Zone in the eastern Indian Ocean' by Pfeiffer et al., https://doi.org/10.5194/cp-2024-25

Dear Editor,

We thank you and the three anonymous reviewers for their helpful comments that will improve our manuscript. Major changes in the revised version will be:

1. A 'Statistics' section will be added in 'Methods' to better explain the various statistical methods used, including the significance tests

2. We will replace 'Intertropical Convergence Zone' with 'Tropical convergence Zone' (TCZ) following Reviewer 2 and clarify that we focus on northward shifts of the southern margin of the TCZ in austral spring (September-November).

3. We will expand the discussion on meridional variability by extending Figure A9 to 2024 using the satellite record, by comparing the satellite record with HadCRUT5 data in the period of overlap, and by comparing the modern Enggano coral record with HadCRUT5.

4. We will provide additional support for the changes in seasonality/increase in austral spring cooling between 1855 and 1917 by adding a table with average coral growth rates, significance tests to assess the similarity/difference between the distributions shown in Figure 8, and by adding the mean seasonal cycle of the Mentawai d18O record before/after 1917 (in the appendix).

Christian-Albrechts-Universität zu Kiel
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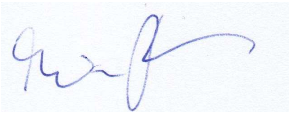
Below are our detailed comments to the reviewer's suggestions (in red).

Sincerely,



Miriam Pfeiffer

Editor's comments:

Thank you for submitting your manuscript to Climate of the Past. I'm opening the online discussion and starting the review process. Please note, that we discourage the use of rainbow colour scales, so can you please look at changing the colour scales used in Figure 6, 10 and A3 when it comes time to revise your manuscript.
Thanks, Nerilie

We will change the color scales.

RC 1

This study aims to understand how the meridional SST gradient in the eastern equatorial Indian Ocean has changed over the past ~200 years. To do so, the author developed a Sr/Ca record using fossil corals collected from Enggano Island for analysis. The authors found that there was an increase in seasonality strength and an earlier seasonal SST maximum between 1855-1917 compared to the modern period and 1823-1854 CE and attributed the change to an earlier onset of austral spring and strengthened SE winds, which consequently imply a northward shift of ITCZ and a stronger meridional SST gradient. On the other hand, there is no conclusive evidence that changes in zonal SST gradient (e.g., IOD) played a role in changing SST in Enggano Island and meridional gradient despite previous suggestions. Therefore, they concluded that the meridional SST gradient and zonal SST gradient are not always coupled and require more analyses on the mechanisms that drive the meridional SST gradient.

I think this new record is a useful contribution to better understand climate variability in the Indian Ocean and complement existing records in nearby areas. I also think the analysis of meridional SST gradient in the NE Indian Ocean is interesting. The screening for coral quality/diagenesis is also extensive. That said, I have some suggestions/comments, that I hope would help improve the manuscript. There are also several inconsistencies within the text and figures/tables, which needs to be corrected. Otherwise, it is difficult to judge the results and conclusion of this study.

We thank the reviewer for his/her efforts to improve our manuscript.

Overall comments:

1. I find referencing the years in reversed chronological order (e.g., 2008 to 1930 instead of 1930 to 2008) confusing. There are also several instances where the years are referred in chronological order instead, for instance L317 "Between 1854 and 1923…". I suggest making this consistent throughout the text, and preferably in chronological order (i.e., older to younger).

We will follow the reviewer's suggestion and reference years in 'normal' chronological order.

2. Within the manuscript, there are multiple instances where statistical significance is mentioned (e.g., 99% confidence levels). However, in most cases, it is unclear how this was determined. Even when a Monte Carlo approach was used, it was also unclear how it was carried out. It would be helpful if this can be clarified.

We will add a section on 'Statistics' in 'Methods' for clarification.

3. The results of this study hinge on an accurate chronology and constraints on the annual cycle. While there are multiple instances within the manuscript where dating uncertainty was mentioned, as far as I can tell, there are no testing of how robust the results were against dating uncertainties. It would be nice to see sensitivity tests to check this. Furthermore, it is currently unclear how the annual cycle was derived (see the comment L181-183 below for more details), which makes me unsure of the results. Additionally, the chronology is derived based on the assumption that the internal chronology and U/Th ages have a 1:1 relationship. While in Figure A6, it shows that they correspond to each other fairly well, there are also instances where the U/Th diverges from the 1:1 line (the 2sigma of KNFa(8/11), KNFa(5/11) do not line up with the regression line). So, I wonder how accurate this assumption is in this case? Moreover, it would be great to provide the estimated extension rates of these corals, just so we can make sure it is indeed possible to estimate monthly SST changes.

The internal chronology is based solely on the seasonal cycle in coral Sr/Ca and is independent from the U/Th estimates. We chose one anchor point (September) in each year as stated in methods (we will omit the reference to Cahyarini et al., 2021 to avoid confusion). The age of the floating chronology (and its uncertainty) is then derived from the regression of the U/Th ages vs. the coral Sr/Ca 'years'. This means that the uncertainty of the floating chronology <u>includes</u> the deviations between the internal Sr/Ca chronology from the U/Th ages seen in Figure A6. We follow a published method (Domínguez-Villar et al., 2012; doi: 10.1016/j.quageo.2012.04.019).

The growth rates of the Enggano corals are very stable, for example KN2 (which is from the same site as KNFa) has an average growth rate of 10.3 ±2.5 mm/year. In the interval with increased seasonal variability from 1855 to 1922, KNFa shows almost the same growth rates (10.8 ±2.4 mm/year) as KN2, while the bottom section of KNFa, which displays reduced seasonal variability, grows a bit faster (11.4 ±2.2 mm/year). This means that the changes in seasonality seen in the corals from Enggano Island cannot be attributed to changes in annual growth rates (lower growth rates could dampen seasonal variability). We will add a table comparing mean annual growth rates in the appendix of the revised version.

Note, however, that Figure 5 shows the <u>raw Sr/Ca data as measured</u>, i.e. each dot represents one actual subsample. We did this to show that the changes in the mean seasonal cycle of

KNFa cannot be attributed to changes in sampling resolution (that may result from changes in coral growth rates). We also show that each of the two modern corals captures the distribution of satellite SSTs at Enggano Island (Figure A7), so they do not under-sample monthly SST variability. We actually put so much emphasis on the distribution of the Sr/Ca data (or the distribution of centered SST data inferred from coral Sr/Ca), because distributions are age-model independent and are not affected by the choice of sub-seasonal tie-points or the accuracy of the U/Th dates.

4. Given that the change in SE wind strength, and the shift in ITCZ are supposed to correspond to changes in the South Asian monsoon, I wonder if it will also be helpful if you can show the South Asian monsoon also changed concurrently with these changes.

The time scales discussed in our manuscript make such a comparison very difficult: the interval from 1823-1917 is just outside the reliable instrumental record, while most proxy reconstructions from this time period have a temporal resolution that is too low for a direct comparison with our data. The HadCRUT5 data we used to estimate the thermal gradient combines land and sea surface temperatures, and therefore has a better data coverage before 1920. The sediment core of Steinke et al. has an exceptionally high temporal resolution. The South Pagai coral record of Abram et al. (2020) ends in 1959, leaving only the Mentawai record, which is far north of Enggano Island and only records the most extreme northward shifts of the TCZ (and in modern climate, the most extreme pIOD events).

An analysis of the Australasian monsoon using 43-years of ERA-40 data does show long-term trends in onset/retreat dates and duration in each of the two monsoon seasons (Zhang, 2009, 10.1007/s00382-009-0620-x). A warm pool SST reconstruction based on corals from various sites of the West Pacific Warm Pool and tree rings from Java (D'Arrigo et al., 2006, 10.1029/2005PA001256), shows cooling before the 1920s, and warm intervals interrupted by short cold spells between 1850-1815. We will discuss these references in the revised version of our manuscript

Specific comments:

L31-32: A 'reference period' needed to compare with in order to claim 'an increase in SST seasonality due to enhanced austral spring cooling'.

We will re-write this sentence to 'The sub-fossil coral indicates in increase in SST seasonality relative to the 1930-2008 period. We attribute this to enhanced austral spring cooling due to stronger SE winds…'

Figure 1: In most cases, the figure is referred in the text when discussing about anomalies during IOD events. So, I wonder if it would be better to change the subplots b-e into OLR and SST anomalies so that they can better serve their purposes?

In Figure 1, we want to show the close relationship between coastal SST and precipitation (using OLR as a proxy for rainfall) off Sumatra. That is why we show SST and OLR side by side. We will better highlight this by adding contours in the panels as suggested by Reviewer 2, and we will improve the discussion of Figure 1 to clarify this point.

L111-L112: It is unclear to me how Aug-Oct temperature and symmetry is inferred based on Figs 2-3 – both do not show mean Aug-Oct temperatures.

We will omit the sentence 'The distribution of mean August-September SSTs is symmetric.' here.

Figure 3: I suggest checking the consistencies between this figure, the caption, and the main text on which months are mentioned and used for analyses. In the text and the caption, Aug-Oct was mentioned, whereas the figure label suggests Sept-Nov. Additionally, the vertical dashed lines don't seem to be located at the same months for the plot of each location in subplot c.

We will check Figure 3 (and the caption) for consistency and correct it.

L154-155: I think the sentence is missing a verb (e.g., were carried out').

Thank you, we will add 'were carried out'.

L181-183: This is actually *inconsistent* with Cahyarini et al. (2021) and Pfeiffer et al. (2021). Both studies tied September to Sr/Ca maxima and May to Sr/Ca minima. But here, it suggests only September was tied to Sr/Ca maxima. Please clarify which way it was done.

We will clarify this. In the present manuscript, we only used September, as there seem to be changes in the timing of the summer SST maxima in the sub-fossil coral KNFa. The choice of the tie-points does not affect our results. For example, the mean seasonal cycle of KN2 matches the SST period chosen for comparison in Cahyarini et al. (2021), Pfeiffer et al. (2022) and in this manuscript (Figure 7). Its magnitude is mainly influenced by the amount of extreme pIOD events in the period of record, since these years have large amplitude seasonal cycles.

We have tested whether the choice of sub-seasonal tie-points would significantly impact the amplitude of the mean seasonal cycle of the modern coral Sr/Ca records, using the same Monte Carlo approach as in Figure 7. They are not significantly different.

L188-195: Fig A6 should probably be referred somewhere here so the readers can go to that figure to get a better sense how this was done.

Yes, thank you.

L233: 'were' -> where

Thank you.

L237: I think the Appendix/Supplementary figures referenced here are incorrect.

Yes, thank you. We will correct this.

L311: repeated '(Fig. A8)'.

Thank you.

L312-320: Should '1854 and 1923' be 1854-1823 instead? Otherwise, this will be referring to the same overlapping period as the previous sentence (1917-1855). Additionally, I would like more quantification on the comparisons between the distributions instead of simply relying on visualizations. Tests such as a Kolmogorov Smirnov test (or its variant) would be helpful here.

We will correct this, it should say '1854-1823'. Thank you.

We will use a Kolmogorov Smirnov test to show that the SST distribution in the 1917-1855 period is different from the modern distribution.

Figure 6: I only see one type of line in subplot (a) with two green and blue lines. I do not see red solid and dashed lines.

Thank you, we will correct the Figure caption.

L350-354: I wonder if there's a more objective way to 'separate' these time periods? Right now, it seems a bit arbitrary and relies on visualization. One suggestion perhaps would be to analyze the wavelet power of annual cycle and identify periods that are weaker to a 'reference period'. This can be pulled out from the wavelet spectra.

The Wavelet Power Spectra include significance tests. We will explain this in the revised version (in a new 'statistics' section in methods), and rewrite these sentences for clarity.

Figure 7: Why is the seasonal cycle shown here span from July to January 2 years later? There are several mistakes in the caption (e.g., 'dashed green lines' for core PB, no explanation of 'dark grey and dashed lines' in subplot a). Additionally, which 'modern' (coral or observation) is used in (d) and (f)?

We displayed the mean seasonal cycle from July to January (+2 years) for better visualization. In (d) and (f) we use the average seasonal cycle of KN2 and PB. We will correct/revise the figure caption.

Figure 8: in subplot c, there is a discrepancy on which years were used for analysis: it was labelled 1917-1869 in the figure whereas in the caption 1917-1855 was referred.

Thank you, we will correct this.

Figure 9: I don't quite understand what "not the large 95% confidence levels of the SiZer test" means. It would also be helpful to explain what the horizontal lines associated with the change point indicators mean. Additionally, there needs to be clarification on how the SiZer analysis was carried out. As far as I recall, SiZer applies a range of Gaussian filters with varying bandwidths and calculate the trends based on those bandwidths. But in the caption, it only mentions about a 21 year running average to show the data and not any other information related to SiZer.

'Not the large..' is a typo, it should say 'Note the large…'. We used the SiZer only to determine the change points, so the bandwidth is not relevant here. In the revised version, we will explain this in a new 'statistics' section in methods.

L440: I am not sure if age uncertainty is the main issue here. By just looking through the KNFa record, there is no 'major' anomalies (<-4C) between 1869-1917. Given that the absolute dating uncertainties are almost <10 years, I don't think age uncertainty is an issue here. In fact, the remaining paragraph does not discuss about age uncertainty. So, I suggest modifying the first sentence of this paragraph.

We will start this paragraph with 'At present, extreme positive IOD events….'

L444-446: I don't think this is an accurate statement. My understanding is that the Enggano record is better in capturing meridional SST gradient compared to previous Mentawai records. So, it is logical that the Enggano record might not detect IOD changes. That said, a comparison between meridional and zonal SST gradients can be achieved by making use of the Enggano record for meridional changes and the recently southern Mentawai record (Abram et al., 2021 Nature) that is supposed to record IOD changes.

The modern Enggano record captures all IOD events. In the 'modern climate' zonal (IOD) and meridional variability are tightly coupled (see Weller et al., 2014), so we cannot distinguish between them. The de-coupling we see before 1917 has no direct analogue in the reliable instrumental record (except HadCRUT5 or GISS), although future projections suggest that meridional and zonal SST variability in the SE tropical Indian Ocean may uncouple (Weller et al., 2014), depending on the evolution of the temperature gradients. This aspect is hard to explain, we will work hard to improve this point in the revised manuscript.

The modern coral d18O record from southern Mentawai (South Pagai) only extends back until 1959 (and has been compared with the modern Enggano coral Sr/Ca record, see Figure S4 in Pfeiffer et al., 2022). The records are very similar, both show the same IOD events, although the South Pagai record shows somewhat larger variability, which Abram et al. 2020 attributed to SST-covariant changes in d18Oseawater/rainfall. The sub-fossil corals from South Pagai published in Abram et al., 2020 do not overlap with the KNFa record, so we cannot compare them directly.

Satellite SST (available since 1982) at Enggano Island shows cooling during moderate and extreme pIOD events, and the modern Enggano coral Sr/Ca records (KN2 and PB) show these events (Pfeiffer et al., 2022). In fact, the distribution of SSTs inferred from KN2 and PB matches the distribution of satellite SSTs (Figure A7), and the modern cores record ALL pIOD events, including the events in the 1960s (Pfeiffer et al. 2022). The South Pagai d18O record also records all these events, but the d18O signal may be amplified by changes in d18O seawater. See Abram et al., 2015 (p 1400, 2nd paragraph):

'At the South Pagai site, the open ocean setting and small seasonal SST cycle mean that signals associated with extreme pIOD events are clearly detected. Extreme events such as 1997 can produce anomalies exceeding -3.3°C in SST, or 0.87‰in coral δ18O. The gridded SST data for this site suggest that while moderate pIOD events coincide with cool anomalies there is limited differentiation of these anomalies from non-IOD years. However, the detection of moderate pIOD events in coral δ18O is clear, most likely due to the additional influence of associated pIOD rainfall anomalies on coral δ18O.'

South Pagai could potentially help to resolve how zonal IOD variability relates to changes in meridional variability in the eastern tropical Indian Ocean as it is located between Enggano and the northern Mentawai Islands. It is the best candidate for a stationary IOD teleconnection over the Past Millennium, as argued in Abram et al., 2015 and 2020, both in SST and rainfall.

In the revised version, we will expand the discussion to briefly explain the South Pagai d18O record. We can discuss the 'youngest' of the sub-fossil records from South Pagai, which almost connects to the bottom of the KNFa record. This core shows a series of 6 pIOD events between 1775 and 1825.

L456: hereinafter, 'foraminifers' should be 'foraminifera'.

Thank you.

L461: Would ($p>0.05$) mean it is not significantly different?

Yes, it should be $p<0.05$.

L461-462: I think it would be helpful to test statistically if the relative abundance of thermocline dwelling forams changed significantly.

Thank you, we will add this.

L464: 'linkedn' -> linked

Thank you.

Figure 11: I wonder if the abundance of mixed layer forams timeseries is needed, since it was never discussed in the text?

We would prefer to show both the mixed layer and thermocline dwelling forams since they come from the same sample. We will add a sentence on the mixed layer forams in the discussion.

Table A1: What do those asterisks next to KNFa(3/11) and KNFa(7/11) mean?

These samples were dated at a later/different date. We will add the calendar dates when the dating was done below table A1.

Figure A6: I don't think the equation displayed here is correct. Plugging in any years prior to 1934.1 will result a negative y, which isn't supposed to happen here.

-1934.1 is the intercept of the linear regression. "y" is the internal chronology [Years] and "x" are U/Th ages [Years CE].
We will re-write the equation as follows:
Internal chronology [Years] = 1.0594 x U/Th ages [Years CE] - 1934.1
$R^2 = 0.99$

L601: As far as I can tell, I don't see any U/Th ages that correspond to 1823 both in the figure and in table A1.

The age of the base of the KNFa chronology is estimated from the regression equation shown in Figure A1. We will delete this sentence here, as this is better explained in section 3.4

L619: '(a)' should be (b) here.

Thank you.