C | A | U Christian-Albrechts-Universität zu Kiel
Mathematisch-Naturwissenschaftliche Fakultät

Prof. Dr. Miriam Pfeiffer | Inst. f. Geow. | Ludewig-Meyn-Str. 10 | 24118 Kiel

Nerilie Abram,
Editor
Climate of the Past

Prof. Dr. Miriam Pfeiffer
Paläontologie und
Historische Geologie

Institut für Geowissenschaften
Ludewig-Meyn-Str. 10
24118 Kiel
Tel.: 0431/880 2855
Fax: 0431/880 5557
e-mail:
miriam.pfeiffer@ifg.uni-kiel.de

Kiel, 19.07.2024

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).

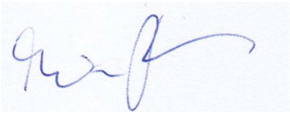
3. We will expand the discussion on meridional variability by extending Figure A9 to 2024 using the satellite record, by comparing the satellite record with HadCRUT5 data in the period of overlap, and by comparing the modern Enggano coral record with HadCRUT5.

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).

C | A | U Christian-Albrechts-Universität zu Kiel
Mathematisch-Naturwissenschaftliche Fakultät

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 2

Overall comments;

This study aims to contribute to the growing number of reconstructions in the Southeastern Indian Ocean region and document how the meridional SST gradient has changed in the past 200 years. To achieve this the authors, develop a sub-fossil coral Sr/Ca record collected from Enggano Island, an island previously used to reconstruct Indian Ocean Dipole variability. The authors found the sub-fossil exhibits an enhanced seasonal cycle between 1855-1917 compared to the modern equivalent and the later 1823-1854 periods. This enhanced seasonal cycle was attributed to an earlier onset of austral spring, and increased SE winds during July-October. This was then attributed to a northward shift in the mean position of the ITCZ and a stronger meridional SST gradient in the eastern Indian Ocean. They conclude that this is unlikely to be associated with enhanced IOD variability as spectral analysis suggests that variability associated with the Enggano coral is mostly interannual, and IOD variability would only impact the IOD season rather than the full seasonal cycle. Based on historical SST products they additionally conclude that the zonal (IOD) and meridional components controlling the shift in the ITCZ are not linearly coupled in the past.

This coral reconstruction is a useful contribution to the regional understanding of the Indian Ocean variability due to the sparse observational record in the region. This record complements previous records in the region, particularly adding to a large reconstruction effort of the IOD. Some of the methodological aspects of this study are excellent, particularly the diagenesis screening which is an excellent example of how to address issues with sub-fossil usage. I do have some concerns with the study, which I believe would improve the manuscript and better align with the knowledge of the community.

We thank Reviewer 2 for his/her helpful comments that help us to improve our manuscript.

Overall concerns;

1. I have an issue with the definition of the ITCZ region. In this region, the Maritime Continent, the definition of the traditional ITCZ does not typically apply. Due to the numerous monsoonal systems that operate in the region, the system should be defined as a 'Tropical Convergence Zone (TCZ) or Tropical Rainfall Belt', as outlined in Geen et al., 2020 (**https://doi.org/10.1029/2020RG000700**). The transition of the monsoons (as the author here is describing) is commonly associated with the global monsoon transition. I would encourage the authors to think about this definition and which they should be using. Additionally, due to the width of the TCZ in this region, I would encourage the authors to instead state this as the Southern Boundary of the TCZ.

We will replace 'ITCZ' with 'Tropical Convergence Zone' (TCZ) and focus on the position of its southern boundary off the coast of Sumatra. This helps us to better describe Figure 1 and to explain our main findings.

2. The main finding of this paper is based on the difference between the seasonal range in the sub-fossil and the modern. There are some issues with this methodology. Firstly, the description of how the age model was constructed is inconsistent, with different explanations of how the age model was constructed. In the modern coral in Pfeiffer et al., 2022 tie points are constructed on both minima and maxima which may make a difference when comparing the seasonal cycle, as according to this paper the maxima temperature is not constrained.

We used only on tie-point in this study, as explained in 'Methods', and we tied it to September in each year. We found this more appropriate as our results indicate potential non-stationarity in eastern tropical Indian Ocean climate prior to 1917, so we were not sure whether we could 'prescribe' modern seasonality. All records shown in this study were processed this way. We also found that the choice of sub-seasonal tie points does not significantly affect our results. For example, the mean seasonal cycle on KN2 matches the SST period chosen for comparison in Cahyarini et al. (2021), Pfeiffer et al. (2022) and in this manuscript (Figure 7). This is because in the modern record, the amplitude of the mean seasonal cycle at Enggano is strongly influenced by the number of extreme pIOD years relative to normal years. Note that the seasonal SST amplitudes of extreme pIOD years are more than twice as large as in normal years. This has a stronger impact on the 'modern' mean seasonal SST cycle than the choice of sub-seasonal tie-points. We have tested this using the same Monte Carlo approach as in Figure 7.

As we were aware of potential impacts of tie-points/interpolation procedures on our interpretation, we carefully evaluated the distribution of the measured Sr/Ca data (this was also done in Cahyarini et al., 2021). The distribution of the coral Sr/Ca data is not affected by age model development, such as the choice of sub-seasonal tie points. After SST conversion, the distribution of the modern data matches the distribution of satellite SST. The changes in distributions we see between 1850 and 1917 in Figure A8 (a larger spread around the median with no/only one outlier) provide strong support for the changes in the mean seasonal cycle shown in Figure 7.

3. I feel that the modern comparison is not sufficiently explored in this paper, particularly towards the detection of IOD events, the authors state that the change in the seasonal variability is not linked to IOD events however state that there are IOD-like events in the coral (which are mentioned in the methods). Additionally, as the main finding is centred around the difference between Mentawai and Enggano a more in-depth comparison would be appropriate.

We will improve the discussion of the modern Enggano record, which shows coupled meridional and zonal variability (the latter associated with the IOD, as discussed in Pfeiffer et al., 2022), and how it compares with the sub-fossil record of KNFa for clarity. In 'modern climate' (1930-present), Enggano Island lies almost in the center of the eastern SST pole of the IOD (90°E–110°E, 10°S–0°). Throughout the satellite period (which only started in 1982), meridional and zonal SST variations remain coupled, and the Enggano corals record the cooling seen during pIOD events (Pfeiffer et al., 2022). This holds back until 1930, when the modern Enggano corals end – there is no change in the relationship between the North-South and East-West SST gradient until this point (Figure 9) (We will add a comparison of the modern Enggano corals and the NS HadCRUT5 temperature gradient in the appendix of the revised version).

Only future projections suggest that meridional and zonal variability in the eastern tropical Indian Ocean may be non-stationary and could uncouple with changes in mean climate (Weller et al., 2014). The sub-fossil coral KNFa from Enggano Island suggests that this may have also happened in the past, i.e. between 1917 and 1855, in an interval at the very end of the historical record of temperature (which is better observed than other climatic parameters). We are confident that <u>the changes we see are driven by changes of the monsoon via stronger SE monsoon winds</u>, as (1) they impact the mean seasonal cycle rather than interannual variability in KNFa, (2) we see a corresponding increase in the meridional SST gradient which is not seen in the zonal gradient, and (3) we see corresponding changes in a very high-resolution sediment core taken off Sumba Island (colder SSTs and a deeper thermocline before 1920).

However, it is at present unclear how the changes in the mean seasonal cycle we see in the KNFa record between 1917 and 1855 feedback on interannual variability and/or the zonal SST gradient in the tropical Indian Ocean. In modern observations, IOD events can be attributed either to greater warming in the western pole of the IOD, greater cooling in the eastern pole, or simultaneous changes that occur in both poles (Jiang et al., 2022; https://doi.org/10.1175/JCLI-D-21-0089.1). Strong cooling in the eastern pole coupled with weak warming in the west is attributed to a strong South Asian summer monsoon (Jiang et al., 2022). We feel that aspects of these modern events may help to explain the KNFa record between 1917 and 1855. However, in the modern climate, these events are part of the IOD spectrum. Moreover, strong upwelling in the eastern pole of the IOD may also trigger pIOD events (Horii et al., 2022; https://doi.org/10.1029/2022GL098733).

We will revise the discussion to better distinguish between modern observations of processes that are attributed to the IOD, and aspects of these that we use to explain the fossil record of KNFa, particularly in the interval from 1917-1855, where the role of the IOD is currently unclear.

Specific comments;

Line 43/44 – I believe that the suite of Abram et al., papers should be included here or in the next line of referencing. Particularly the paleoclimate perspectives paper

We have structured the introduction into studies based on observations and paleo data, and we reference the papers of Abram et al. in the latter. However, we are happy to include the 2020 paper in line 43/44.

Line 49 - As I have stated above I question the use of the word ITCZ as the proper definition of this region should be classified as a Tropical Rainfall Belt (TRB) or Tropical Convergence Zone (TCZ). The Weller and Cai., 2014 paper refers to the ITCZ the author has described there as the Oceanic Tropical Convergence zone (OTCZ), and monsoonal papers refer to this region at the TRB as do other paleo papers.

We will use 'Tropical Convergence Zone' (TCZ). Thank you.

Figure 1 – in the caption the author brings to attention the 27.5 and 28°C isotherms however doesn't highlight them in the figure. This would be helpful as this could be a key component of the paper. Additionally, as the Weller et al., 2014 paper states the 27°C isotherm location is very similar to the North-south gradient this could be a good point of comparison.

We will add contours to delineate the SST isotherms in Figure 1.

Figure 3 – Panel C would be helpful to have the little icons on the figures as well as the location of each, so it is intuitively easier to determine which location is which. Additionally, it would be more intuitive if the plots were ordered from West to East (i.e. Northern Mentawai should be first) as this would better connect to panel a.

We do not quite understand the first part of this comment: panel C in figure 3 shows the icons indicating the location of each SST grid, together with the coordinates of each SST grid.

We chose to order the panels starting with Java because coastal upwelling starts off Java and then progresses further north. English is read from 'left to right'.

Line 104 – This line suggests that the SST reaches the entire Mentawai Islands in October, however, the cool temperatures reach the Southern Mentawai Islands earlier allowing for the capture of the full pIOD associated upwelling. At South Pagai the full spectrum of moderate and positive IOD events are captured appropriately, South Pagai and Enggango should be very similar.

We will rewrite this sentence to 'It reaches Enggano in July, and extends to the northern Mentawai Islands in October. The South Pagai and Enggano records are indeed very similar (Pfeiffer et al., 2022, Figure S4). Unfortunately, the modern South Pagai record only extends back until 1959, and the sub-fossil coral records shown in Abram et al. (2020) do not overlap with the Enggano record.

Line 109 – the phrase Meridional gradients in SST are particularly steep is confusing. Meridional gradients in SST suggest that the author is talking about the difference between two locations within the region, however, it seems that they are simply talking about the location of Enggano and that the seasonal variability is drastic as there is a steep/speedy transition in temperature?

No, we do not mean to say that the seasonal variability at Enggano is drastic. We mean to say that the magnitude of cooling seen during the SE monsoon changes profoundly over short distances from northern Java to southern Sumatra, encompassing the location Enggano Island, as does the mean seasonal cycle of SST. This means that relatively small changes in the strength/extend of the SE winds should be seen in the magnitude of austral spring cooling/ the amplitude of the mean seasonal cycle at Enggano Island. We will re-write these sentences for clarity.

Line 181 – Some clarification here would be good, the methods in Cahyarini et al., 2021 and what is stated here differ. If the core is tied only to September, it would be appropriate to remove this reference here, if the coral is also tied to the minima values then this would negate some of the discussion later on about the change in the timing of the offset. Additionally in Pfeiffer et al., 2022 (where the original modern corals are published) it is stated that the maxima are tied to May which if only the sub-fossils are not tied would potentially influence the interpretation. Could the author comment on this?

In this study, we used only 1 tie-point (September) for all cores. The choice of the sub-seasonal tie-point does not significantly impact the amplitude of the mean seasonal cycles of the Enggano corals. See also our previous comments. We will remove the reference to Cahyarini et al., 2021.

Line 297 – why would this be misleading?

We will omit this sentence and focus on the fact that we use two modern coral Sr/Ca records to assess how reliable a single coral records SST variability at Enggano Island.

Line 300 – the definition of extreme pIOD events here is different to that stated elsewhere, i.e. in Abram et al., 2015 where the pIOD events of 1963, and 1967 are defined as moderate events. Another inconsistency is the lack of picking up the 1982 moderate event in the Engagno coral.

The events of 1963 and 1967 were defined as 'extreme' in Pfeiffer et al., 2022 based on the fact that the cooling exceeds the cooling seen in 2006, which has been described as 'extreme' in Yang et al., 2020. The 1982 event is picked up as a 'moderate' event (Pfeiffer et al., Figure S4).

The extreme IOD events in the 1960s are underestimated in historical SST products such as ERSST5 and HadISST, as these do not adequately capture non-linear ocean-atmosphere feedbacks in the eastern Indian Ocean (Yang et al., 2020, Pfeiffer et al., 2022). Abram et al. (2015 and 2020) relied on stable oxygen isotope records which are also impacted by changes in the isotopic composition of seawater/rainfall that co-vary with the IOD and inflate the IOD signal in coral d18O. She assumed that the rainfall contribution remained stationary over time, but she could not independently assess how the magnitude of cooling seen in the IOD years of the 1960s compares with historical SST products.

Line 307 – this should be 'likely' due to vital effect, or by the intercolonial differences in Porites

We will add 'likely'.

Line 311 – there are two (Fig. A8) here.

We will delete one, thank you.

Line 314 – As stated in line 313 above, the author lists the timing of the strong positive skewness during extreme pIOD events period, this would be helpful in the example without extreme positive IOD events to allow the reader to immediately compare.

We will re-write these sentences to focus on (1) extreme IOD events and skewness (2), symmetric distributions in periods without extreme pIOD events.

Lines 310-320 – this whole region of the test there are inconsistencies in the periods instances where the period stated ranges from (oldest – youngest or youngest- oldest) It is more intuitive to have all periods stated from oldest – youngest;. i.e. line 316 should be 1855-1917.

We will remove the inconsistencies and refer to all time periods from oldest to youngest.

Line 315-310 – there is some confusion in this section, only like states a larger spread between 1917-1855, and the next line states that between 1854-1923 the spread reduces. Perhaps the author meant 1854-1823 otherwise we would be talking about the same period.

We meant the 1823-1854 period. Thank you.

Line 324 – I believe as the basis of this paper it would be pertinent that this section be expanded on. Firstly in Figure A9; If this analysis is based on the Weller et al., 2014 papers, the Meridional SST gradient boxes are different to those displayed in this figure and also in Figure 9. If the relationship is based on this relationship and the occurrence of extreme TCZ shifts in the future it would be good to adjust the boxes to match. Additionally, extending the relationship between the North-south gradient and local SST at Enggano between the periods of 2005-2020 would further allow for comparison and give a longer period of 'modern testing', if the coral is strongly related to SST this would be a fine comparison. Perhaps this could be added as a panel in the figure?

The SST gradient boxes in Figure A9 match the boxes in Figure 9 and in Weller et al., 2014. We gave incorrect coordinates (100°E instead of 110°E) We will also expand the Figure to 2024 using the satellite record (note, however, that the coral cores were drilled in 2008 and cannot be extended). In the satellite period, the HadCRUT5 N-S gradient tracks the satellite SST gradient (r=0.83).

Additionally in Figure 9, the Authors have calculated the North-South gradient using the HadCRUT5. It would be interesting to see if the relationship shown in Figure A9 holds up with this extended period, i.e. how does this compare to the coral?

We will make a separate panel comparing the HadCRUT5 gradient with the modern Enggano corals back until 1930. The correlation is weaker compared to the satellite period, but stable and significant (r=0.46, n=79, $p<0.5$). The sub-fossil coral cannot be directly correlated dur to dating uncertainties.

Line 350-355 – This analysis is very interesting; my major question is whether the choice of period changes the analysis. Particularly with the distribution analysis in Figure 8. Figures 8a and b are based on 73 years' worth of data, while figure 8c is based on 48 years of data. If these could be compared on the same number of years this would be more comparable.

Additionally, is there a way to improve the statistical comparison of these, rather than relying on the visual comparison?

In Figure 7, we performed a Monte-Carlo based test to show that the changes seen in the mean seasonal cycle are significant, as in Pfeiffer et al., 2022. In the revised version, we will add a 'statistics' section in 'Methods' to better explain the calculation.

Figure 8 a and b: the distribution of the modern coral data does not change if we only use the most recent 48 years of data (i.e. back until 1960). There are no extreme IOD events prior to 1961, and the spread around the median in these non-extreme pIOD years does not change back until 1930. Please compare the violin plots of the 1989-1970 period and the 1949-1930 period in Figure A8.

We will use a Kolmogornov-Smirnov test to show that the distributions shown in Figure 8 are (I) not significantly different (KN2 and PB), (II) significantly different (KN2/PB and KNFa), following the suggestion of reviewer 1.

Figure 7/8 – to allow for better comparison could the author set up the figures so that the figures in Figure 8 are in the same layout as Figure 7. Additionally, the periods are confusing. KNFa changes from 1917-1855 to 1917-1869 in Figure 7 and Figure 8 respectively.

We will re-arrange the panels in Figure 8 and check for consistency of the time periods in Figure 7 and 8.

Line 395 – I believe from reading the various Weller papers that there are instances in the recent period where the occurrence of a pIOD event is not associated with a northward shift in the TCZ, for example in 1982 where the meridional temperatures did not change significantly and thus the TCZ was not classified as an extreme northward shift.

We will add a sentence mentioning instances were meridional variability did not track zonal variability. 1982 is indicated in Figure A9 (we will improve readability in the revised version).

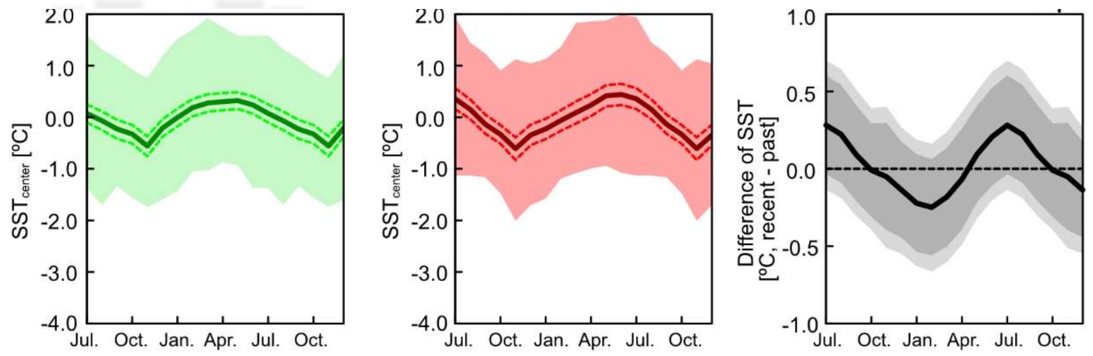
Section 5.5 – Comparing the records in the SE tropical Indian Ocean would suggest the authors would like to encompass other records of coral-based variability in the region. Additionally including reconstruction of both extreme IOD and pIOD. In Abram et al., 2020 – Coupling of Indo-Pacific climate variability over the last millennium – there are several pIOD events suggested between 1850-1900 which are picked up in the Mentawai coral reconstruction. As the periods are the same it would be interesting to know if the Enggano coral also picks up these events. Additionally, to make the same comparison between Mentawai and Enggano I would suggest the authors do a similar mean seasonal cycle analysis as done in Figure 7 for Mentawai. This could simply be an appendix figure to show there is no significant difference between the Mentawai periods if this is true.

The sub-fossil South Pagai/Southern Mentawai coral d18O records published in Abram et al. 2020 do not overlap with KNFa. The youngest portion of one of these records ends in the 1820s, when the KNFa record ends. This record shows 6 pIOD events, which were not classified as 'extreme' (see Figure 2a in Abram et al. 2020). We will mention this in the discussion of the revised version.

The long DMI reconstruction spanning 1850-2020 shown in Figure 2 of Abram et al., 2020 is calculated from a larger set of coral d18O records. It includes 2 cores from the Seychelles (Western Indian Ocean): Charles et al. 1997; Pfeiffer & Dullo, 2006; and 2 cores are from Indonesia (eastern Indian Ocean): Bali (Charles et al., 2003), and Mentawai (Abram et al., 2008). All these records are based on coral d18O, and are interpreted to reflect combinations of SST and d18Osw/rainfall. Abram et al, (2008) describes the calculation of the coral DMI index. The identification of IOD events in this DMI reconstruction includes the assumption that the SST-rainfall teleconnection remained stationary in the eastern and western Indian Ocean.

In our study, we use coral Sr/Ca to focus on SST variability. We therefore preferred to use only the Mentawai coral d18O record for comparison, to have a better understanding of what we are seeing in the eastern Indian Ocean. The mean seasonal cycle of the Mentawai record prior to 1917 is not significantly different from the modern period. Extreme pIOD events in this record are few (1997, 1994 and 1961) and are not seen in the skewness of the 99% percentiles in monthly September-November SSTs.

Below: Mean seasonal cycle of SST inferred from the from Mentawai d18O record. Left: 1997-1918, Middle: 1917-1860 (end of record), right: difference between the mean seasonal cycles. Significance was assessed with Monte Carlo as in Pfeiffer et al., 2022.



Line 440-445 – the first sentence in this paragraph does not connect to the remaining paragraph. The age uncertainty is probably not the issue here and as such if the authors are trying to state that the extreme positive event is not seen because of the higher SST variability (likely reflecting variability closer to 7°S as stated earlier and the extreme pIOD is more similar to regular cooling) that should be emphasized. However, I am confused by this as earlier in the text the authors state that there are pIOD-like events (ones that match the magnitude of 2006, in line 330) so if this is true these events should not be picked up in the cores.

We will delete the first sentence of this paragraph. We meant to say that with a precise age model, we could identify the year 1877 in the Enggano Sr/Ca record, and discuss its SST anomaly. But the important point here is that because of the higher SST variability/regular cooling at Enggano Island in the 1855-1917 period, pIOD events are hard to identify.

We noted, however, that some years in the Enggano record from 1855-1917 are as cold as 2006. We are not sure whether these cold years had a larger-scale impact on circum-Indian Ocean climate (comparable to present-day IOD events). We will re-write the discussion for clarity.

Line 461 – the t-test indicates this is not significant, perhaps the author meant less than.

We made a typo, the arrow points in the wrong direction.

Line 465 – the use of fully in this line is unnecessary.

We will delete ‘fully’.