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Nerilie Abram,
Editor
Climate of the Past

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Revised manuscript titled 'A sub-fossil coral Sr/Ca record documents northward shifts of the Tropical Convergence Zone in the eastern Indian Ocean' by Pfeiffer et al., https://doi.org/10.5194/cp-2024-25

Dear Editor,

We have revised the manuscript as outlined in our response to the reviewer comments, which are appended again at the end of this letter.

Major changes in the manuscript text are:

1. 'Intertropical Convergence Zone' has been replaced with 'Tropical convergence Zone' (TCZ) following Reviewer 2. We clarify that we focus on austral spring (September-November) and on northward shifts of the southern margin of the TCZ. The title of the manuscript has been changed accordingly.

2. We omit misleading references on the age model reconstruction of the coral data.

3. A 'Statistics' section has been added in 'Methods' to better explain the various statistical methods used, including the significance tests.

4. We have expanded the discussion on the relationship between meridional and zonal SST variability and modified the text for clarity (in particular in sections 5.2-5.5). This includes a more extensive discussion of other coral reconstructions of the Indian Ocean Dipole.

5. Ages/time intervals are given from 'old' to 'young'.

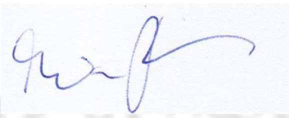
6. We have carefully checked text and Figure captions for inconsistencies and corrected them.

Figure and Tables:

1. Rainbow colors have been replaced (Figure 6, 10 and A3).
2. We have added the 27° and 28°C contours in Figure 1 as well as boxes to indicate the regions used for calculating the N-S SST gradient in the eastern Indian Ocean following the work of Weller and co-workers.
3. We have modified Figure 8 to better align with Figure 7 and added percentile plots comparing the distributions of the coral data shown in a-c.
4. We have added an additional figure showing surface winds and outgoing longwave radiation in September (all years and extreme pIOD events) (Figure A1)
5. We have extended Figure A9 to 2023 using the satellite record of SST. We also compare the meridional gradients calculated from the satellite record with HadCRUT5 data in the period of overlap, and we compare the modern Enggano coral record with the HadCRUT5 N-S SST gradient back until 1930.
6. We added a new Figure comparing the mean seasonal cycles of the Mentawai d18O record (modern and pre-1917) (Figure A11).
7. We added a table showing coral growth rates (Table A1).
8. We have performed a Kolmogorov-Smirnov test to confirm that the distributions of the modern and 1855-1917 coral data are different (Table A3)-
9. Table A5 shows results of Kolmogorov-Smirnov test comparing coral SSTcenter and modern satellite SSTs at Enggano (5°S) and at 7°S. This supports our interpretation of Figure 8.

Below are our comments to the reviewer's suggestions from our previous rebuttal letter (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 includes 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 raw Sr/Ca data as measured, 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.

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 the changes we see are driven by changes of the monsoon via stronger SE monsoon winds, 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).

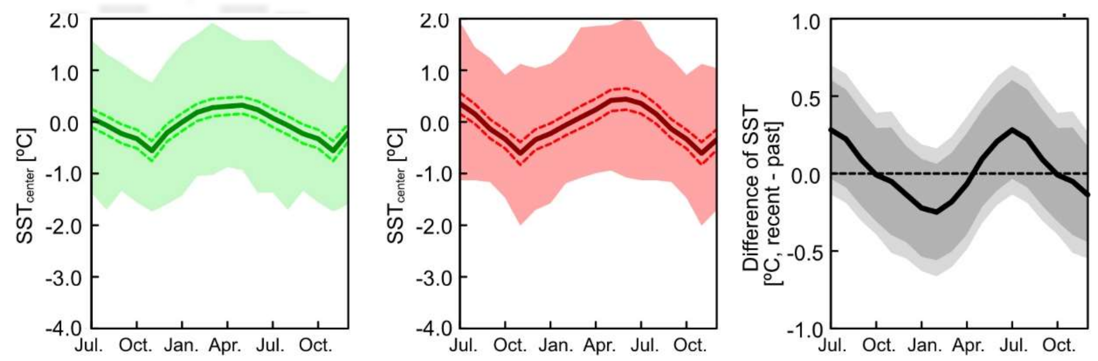
Section 5.5 – Comparing the records in the SE tropical Indian Ocean would suggest the authors would like to encompass other records of coral-based variability in the region. Additionally including reconstruction of both extreme IOD and pIOD. In Abram et al., 2020 – Coupling of Indo-Pacific climate variability 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'.

RC3

The manuscript by Pfeiffer et al. presents a monthly coral Sr/Ca record from the eastern Indian Ocean from a fossil coral colony spanning portions of the 19th and 20th centuries. The authors compare this record with previously published coral Sr/Ca records from modern corals at the same site (Enggano Island) and with a published d18O record from farther north at Mentawai to examine past changes in meridional SST gradients related to ITCZ-induced upwelling. The authors find that there was an increase in SST seasonality and an earlier onset of maximum SSTs from 1917-1855 at the fossil coral site, which they conclude is related to stronger SE winds due to a northward shift in the ITCZ that results in stronger seasonal upwelling. They argue that this stronger seasonality is not present in the published Mentawai coral record farther north, concluding that the ITCZ does not shift beyond the Mentawai site. The authors conclude that the lack of seasonality at Mentawai allows for a stronger response to interannual IOD-related upwelling events and results in larger meridional SST gradients between the two sites from 1917-1855.

Overall, the manuscript provides an important new record in the eastern Indian Ocean that allows a more complete examination of meridional SST gradients in a crucial upwelling region. The authors are also very rigorous with their assessment of diagenesis and secondary calcification. However, there are instances where the authors need to improve clarity in their methodology, writing, and figures to allow for full assessment of the manuscript.

We thank the reviewer for his helpful comments that improve the clarity of our manuscript.

General Comments

Methodology:

- The authors say they developed the age model using 1 tie point following Cahyarini et al. (2021), but that paper used 2 tie points. Using 2 tie points seems important given the focus on seasonal variability.

We used only one tie point for all the records presented (KN2, PB and KNFa). We will delete the reference to Cahyarini et al., 2021. Given the changes seen in seasonal SST variability in the KNFa record, this is a more conservative approach (see also our response to reviewer 1 and 2), as we do not prescribe 'modern' seasonality.

Using two tie-points does not significantly impact the amplitude of the mean seasonal cycle at Enggano Island, which mainly depends on the number of extreme pIOD events in a given time period (the seasonal cycle in these extreme years is more than twice as large as in non-IOD years). Cross-checking with the distributions of the Sr/Ca data (which are not impacted by the age model/choice of tie points) supports our conclusions. We have now conducted a Monte Carlo test to assess the influence of the number of tie points on the amplitude of the mean seasonal cycle, analogues to Figure 7. The mean seasonal cycles obtained with 1 or 2 tie-points are not significantly different from each other.

The strength of coral Sr/Ca is unclear since the modern coral records used for comparison have weak monthly calibrations with r2 values of only 0.45 and 0.5. No calibration comparisons were provided in this manuscript, or in the original publication (Pfeiffer et al., 2022) to assess the Sr/Ca proxy and determine its reliability across months and seasons.

The r-values of the monthly correlations are all larger than -0.65 and highly significant. This is good for a site with a low-amplitude mean seasonal cycle (where intraseasonal variability, which is not tied to the monthly SST record, is comparatively large). The annual mean correlations are higher, although the sample size is much lower, and the slope values of the Sr/Ca-SST regressions of all equations vary around -0.06 mmol/mol per 1°C. Below we re-display table 1 from Pfeiffer et al., (2022):

Coral core	Regression equation [Sr/Ca = slope(± standard error) x SST + intercept(± standard error)]	r (r^2)	p	σ	n
Annual					
PB	Sr/Ca = − 0.061(±0.01) × SST + 10.607(±0.30)	0.76 (0.58)	≪ 0.01	0.014	26
KN2	Sr/Ca = − 0.075(±0.01) × SST + 11.077(±0.37)	0.76(0.58)	≪ 0.01	0.024	26
Enggano	Sr/Ca = − 0.068(±0.01) × SST + 10.821(±0.28)	0.81(0.66)	≪0.01	0.015	26
Monthly					
PB	Sr/Ca = − 0.045(±0.002) × SST + 10.119(±0.07)	− 0.71(0.50)	≪0.01	0.038	322
KN2	Sr/Ca = − 0.054(±0.003) x SST + 10.257(±0.09)	− 0.71(0.50)	≪0.01	0.046	322
Enggano	Sr/Ca = − 0.047(±0.003) × SST + 10.208(±0.08)	− 0.67(0.45)	≪0.01	0.035	322
Mean Equation (Corrège, 2006)	Sr/Ca = − 0.0607 × SST + 10.553				

Table 1. Linear regression equation and correlation coefficient between annual mean and monthly coral Sr/Ca and NOAA OISSTv2 centered at Enggano Island (5°S, 102°E) for the time period 1982–2008 and the mean equation from[17] for comparison. r(r^2) is the correlation coefficient, p is the p-value and σ is the standard deviation of the regression.

In Pfeiffer et al. (2022), the modern Sr/Ca record was compared with various SST products. We compared time series, scatter plots and distributions. We used the monthly and the mean September-November Sr/Ca data. The data was centered and converted to SST using a mean Sr/Ca-SST dependence of -0.06 mmol/mol per 1°C following Watanabe and Pfeiffer (2022). Uncertainties were computed following Watanabe and Pfeiffer (2022).

We found that the coral Sr/Ca record tracks the variability seen in satellite SSTs and in SSTs from ocean reanalysis products that capture the non-linear ocean-atmosphere interactions in the south-eastern equatorial Indian Ocean. Historical SST products interpolated from sparse data underestimate IOD-induced cooling (as demonstrated in Yang et al., 2020), and show weaker cooling compared to the coral record. Below we re-display Figure 3 of Pfeiffer et al. (2022) that compares monthly coral Sr/Ca data from Enggano Island (composite of KN2 and PB, centered and scaled using -0.06 mmol/mol per 1°C) with satellite SST (green, top), SSTs from ocean reanalysis products (left, red colors) and historical SSTs interpolated from sparse data (right, blue colors) are shown for comparison.

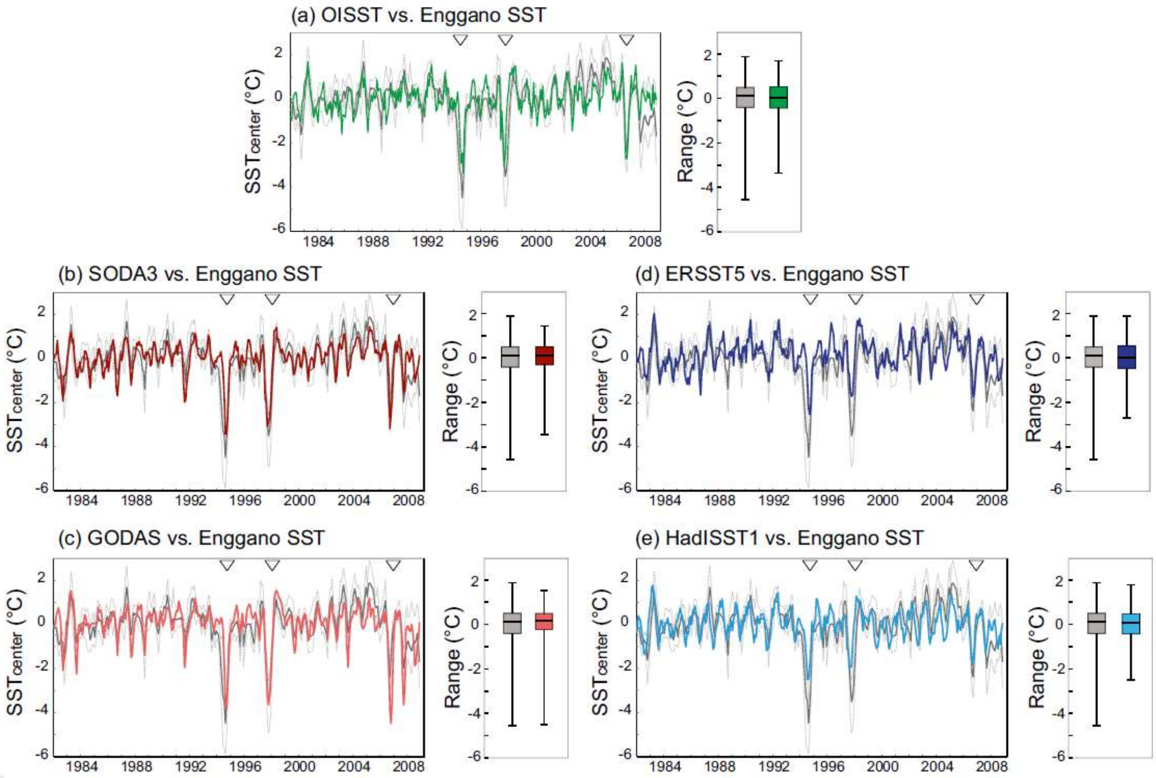


Figure 3. Monthly instrumental SSTs from various products and their SST range (boxplots showing median, interquartile range and maxima/minima as whiskers) compared with the monthly Enggano SST record (in grey) for the time period of 1982–2008. (**a**) OISST (green), (**b**) SODA3 SST (dark red), (**c**) GODAS SST (light red), (**d**) ERSST5 (dark blue), (**e**) HadISST1 (light blue). Arrows mark extreme pIOD events of 2006, 1997 and 1994 discussed in[11]. All time series have been centred to their mean.

- More description of methodology is also needed to assess the gradient calculations, such as the spatial areas averaged for use in the calculations.

We will add a section on 'Statistics' in 'Methods' in the revised manuscript. In addition, we will expand the analysis of the SST gradients following the suggestions of reviewer 2. This includes an assessment of the 'modern' meridional SST gradient to 2024 using satellite SST data, and a comparison of this satellite record with HadCRUT5 temperature data that is used to assess long-term trends. We will also compare the modern Enggano coral record with the HadCRUT5 temperature gradient.

Figures:

- Many of the time periods shown in the figures do not correspond with the years discussed in the main text

We will check/correct Figures and text for consistency.

- Often figure captions reference lines or data that is not shown on the figures

We will check/correct Figure captions.

- Specific months that define austral spring are often not defined

We will define austral spring months wherever applicable.

Data Interpretation:

- Some of the conclusions made by the authors seem to be based on a visual assessment rather than statistical analysis (for example the discussion of multi-decadal variability in temperature gradients). It would be good for the authors to provide quantitative support for all analyses of the records.

We used a Sizer test to determine the change points in the meridional and zonal SST gradients. However, we did not specifically investigate multi-decadal variability and we will omit this in the revised paper. We will use a Kolmogornov-Smirnov test to show that the distributions shown in Figure 8 (modern vs. 1917-1855) are significantly different. We will also compare the mean seasonal cycles of the Mentawai d18O record before and after 1918 (analogues to Figure 7). The Mentawai d18O record does not show an enhanced seasonal cycle between 1855 and 1917 (see our response to reviewer 2 for illustration).

- One of the authors' primary conclusions is that the lower seasonality of the Mentawai record compared with Enggano from 1855-1917 indicates a northward shift in the ITCZ. The way this conclusion is discussed throughout the manuscript would benefit from improved clarity. At first this conclusion was unclear to me given that the ITCZ migrates to the northern hemisphere annually, moving northward of the Mentawai site. I now realize that the authors are discussing the southern margin of the ITCZ shifting northward, strengthening winds and increasing upwelling, which would impact Enggano more strongly than Mentawai. The authors should clarify this point throughout the manuscript to make sure the reader understand how this mechanism differently impacts the two sites. I also suggest comparisons to monsoon wind strength and ITCZ position, and a schematic to visualize the proposed mechanism. This would improve clarity and understanding for the reader.

We will revise the discussion for clarity. We will make it clear that we focus on austral spring season throughout the manuscript. We will discuss the position of the southern margin of the Tropical Convection Zone (TCZ, following the suggestions of reviewer 2) in austral spring. We will add SST contours in Figure 1. The Mentawai record is compared to delimit how far northwards the southern margin of the TCZ shifted in certain years in austral spring (it shifted to the north of Mentawai in 1997, 1994, 1961 and 1877; however, it mostly remained south of Mentawai between 1917 and 1855). In the appendix, we will add a Figure of SST/surface winds and OLR/surface winds in austral spring, for the same years as shown in Figure 1.

Detailed Comments

28: provide more specific GPS coordinates for coral sites (at least two decimal places)

In the abstract, we only want to indicate the location of Enggano Island, as this is a small Island that most readers will not be familiar with. We will include the GPS coordinates of the sample sites in section 3.1 (Coral collection).

PB: 05.27.88S/102.22.21E
KN2 and KNFa: 05.21.71S/102.21.51E

43: change to "a zonal mode characterized by a reversal"

Thank you.

47-48: Define the months you are referring to when you say “austral spring”. Make sure this is defined throughout manuscript.

We will do this, and we will use September-November throughout the manuscript.

47-48: I’m a little confused about the reference to Figure 1 here. It seems that the sentence is talking about seasonal northward shifts of the ITCZ driving changes in SST gradients, but Figure 1 is related to changes in SST gradients induced by IOD+ events. Either the text should be modified to more clearly discuss the Figure, or the Figure should be modified to show the seasonal ITCZ shifts. If the authors are trying to use Figure 1 to demonstrate the influence of strong positive IOD events on the meridional SST gradient, I suggest more clearly discussing the differences between panel a compared with b-e.

At present, meridional and zonal variability in the equatorial Indian Ocean is tightly coupled (see Figure A9) – the northward shift of the TCZ seen in these panels therefore normally corresponds to a pIOD event. We will revise the text to explain this more clearly.

56: change to “which may shift the ITCZ position”

We will write ‘which may shift the TCZ position’ following reviewer 2.

59: I suggest outlining the ITCZ region in all panels to better show the northward shift

We will add contours in Figure 1.

81: In Figure 1 caption, define “Austral spring”

We will define ‘austral spring’ as September-November.

84: Label the contour lines for OLR <240 M/m2, and for the 27.5 and 28ºC contours. Also label the latitude of the ITCZ

We will add contours. Following reviewer 2, we will focus on ‘the southern margin of the TCZ’.

90: In Figure 2 state months that define “Austral fall”

We add the months defining austral fall.

93: In Figure 2 say “AVHRR OI SST” to be consistent with other figure captions.

We will add ‘AVHRR’.

97: State lat/lon to two decimal places

We will add the decimals.

107: state months for austral spring

We will state the months.

117: Which panels of Figure 1 are you referring to? There does not appear to be cooling to 25ºC (mostly down to 25.5ºC), nor does the cooling seem to consistently extend to the equator.

We will add contours in Figure 1 for clarity, and refer to Figure 3 (panel c) for the magnitude of cooling.

178: How many samples were run to determine the RSD%? State n value

We routinely measure 11 samples, then re-measure the 1st sample of this batch. In addition, we re-measure 6 samples at the end of each day (after 170 samples). So, for the 1598 samples of KNFa, we had >180 replicates.

181: 1 tie-point in September is not consistent with Cahyarini et al. (2021) who used two tie points per year (one in September and one in May). Did you use one or two tie points?

We used one tie-point, we will delete the reference to Cahyarini (2021) here.

204: The modern coral calibration of the Enggano site from Pfeiffer et al. (2022) yield an average monthly slope of -0.047, which is considerably shallower than the slope used in this manuscript for calibration purposes. The authors should use the modern coral slopes from their coral sites.

The modern corals were calibrated at monthly and annual mean time scales (see table 1 in Pfeiffer et al., 2022, copied into this rebuttal), the slopes scatter around -0.06 mmol/mol per 1°C (as expected, Watanabe and Pfeiffer, 2022 have shown that coral Sr/Ca-SST calibrations typically range from -0.04 to -0.08 mmol/mol per 1°C, with an average slope of -0.06 mmol/mol per 1°C; the spread reflects uncertainties in many sources, including the age model of the coral and the instrumental data used for calibration).

The range of monthly and mean seasonal September-November SSTs inferred from the modern corals was consistent with satellite and reanalysis data of SST after scaling the Sr/Ca ratios with -0.06 mmol/mol per 1°C (see Pfeiffer et al., 2022, Figure 3, which we copied into this rebuttal, and Figure 4). The slope of the monthly calibration includes sub-seasonal age model uncertainties which reduce the correlation coefficient, and as a result dampen the slope of the linear regression.

I also wonder how reliably the Enggano site can resolve SST variability using the Sr/Ca proxy at sub-annual timescales. The monthly calibrations presented in Pfeiffer et al. (2022) only have r^2 values of 0.45 to 0.5, which is low for a monthly calibration. The authors should show the calibration data from the modern coral records (Sr/Ca vs. OISST in scatter plots and timeseries) to discuss the strength of the Sr/Ca proxy on monthly timescales at this site. This comparison was not available in the original publication and may help identify whether certain months are more strongly reflecting SST variability than others.

See our comment above. We did compare the time series of monthly coral Sr/Ca data (after scaling it to SST using the mean of published calibration slopes) in Figure 3 of Pfeiffer et al., 2022 (copied into this rebuttal). As the Sr/Ca data in this plot was NOT fitted to the SST records (which we would do if would use a regression equation that actually matches the

Sr/Ca data to the SST series it is compared to), this is strong evidence that Enggano Sr/Ca tracks monthly SST variability.

233: change "were" to "where"

Thank you.

237: This sentence references Figures S5 and S7 which were not provided with this manuscript and do not seem to correspond with A5 and A7, making it difficult to evaluate the manuscript here.

Thank you. We will reference Figure A6, and delete S5 and S7.

245-246: Did you re-drill/re-analyze this section to ensure that the signal is replicable?

We re-measured the sample solution, checked the Ca concentration of the sample solution and the standards bracketing the sample batch for drift. We did not see anything unusual. We also investigated the section via SEM and found no evidence for anomalous growth, diagenesis, bioerosion or any other inclusions in the coral skeleton (note that we can visualize and investigate the actual drill hole with our SEM). We did not re-sample this section, as from our experience, coral Sr/Ca data replicates unless we can 'see' that something is wrong (in the SEM or in the measurement protocol). It would be worrisome if this were not the case.

A sub-fossil South Pagai record published in Abram et al. (2020) shows 6 pIOD events between 1775 and 1825 (Figure 2 of Abram et al., 2020). We will add this in the discussion of the revised manuscript.

289-290: This sentence implies that this manuscript demonstrated a strong Sr/Ca and SST calibration in the KN2 and PB records. Though Pfeiffer et al. (2022) is cited at the end, the sentence is long and this statement is far removed from the in-text citation. I suggest the authors re-write this sentence to more clearly indicate this conclusion is based on published work.

We will re-write this sentence.

334: How are you assessing that the seasonal variability is weaker than interannual variability? It seems that in the modern records, there are more periods with significant seasonal variance compared with interannual. In addition, the magnitude of shading looks similar between the significant seasonal and interannual periods.

The Wavelet Power Spectra of the modern corals show IOD events as localized concentrations of power. As these come with strong fall cooling (intraseasonal) causing an inflated seasonal cycle on interannual time scales, we can see concentrations of power ranging from intraseasonal to interannual. In the revised version, we will explain how wavelets show IOD events for clarity.

342: red lines are not shown in figure

Thank you. We will correct the figure caption.

355-356: Which of the two modern records was used to calculate the difference in mean seasonal cycles? PB or KN2? Make sure to clarify here and in the Figure 7 caption.

We used the mean of both records. We will add this in the caption.

366-372: A schematic would be useful to visualize the mechanism you are proposing. The text should also be modified to make clear that the authors are discussion a northward shift in the southern margin of the ITCZ. For example, the northern edge of the ITCZ migrates to northern latitudes annually in July-September. It should move northward of the Mentawai records. The authors should clarify the focus on the southern portion of the ITCZ when discussing their proposed mechanism for a northward shift that does not reach Mentawai while impacting Enggano.

We will clarify that we focus on the southern margin of the TCZ in austral spring (see also our comments to reviewer 2). We will add plots showing SST and wind/OLR and wind in the Appendix.

379: It would be helpful to add a comparison to the Mentawai record in Figure 7 or in the supplementary material to support the discussion in section 5.3. Also make sure to keep the y-axis scaling consistent across all panels to facilitate easier comparison of the magnitude of the seasonal cycles. Currently the difference plots have different scaling that exaggerates the seasonality. I found this confusing because the difference plots at first glance look as if the magnitude is larger than the variability depicted in panels a-c.

We will add the mean seasonal cycle of the Mentawai record in the appendix (as shown in this rebuttal). It does not show a significant increase in seasonality before 1917 (as shown in the wavelet power spectrum, see Figure 10). The y-axis of the difference plots was inflated for better visualization. We will add this in the figure caption to avoid confusion.

389: For panel 8c, why is the time period depicted 1917-1869 rather than 1917-1855 as is discussed in the text and figure caption? Make sure to be consistent. Also make sure to explain the lat/lon differences between panels in the figure caption.

We will correct/improve the Figure caption and labels.

398-400: State the spatial domains (lat/lon) used to calculate the meridional and zonal gradients. It would also be good to show these regions on a map (Fig 1 or 2).

We will add the spatial domains and show the regions in Figure 2.

405-406: Did you conduct any quantitative assessments of the variability, such as spectral analysis or other spectral methodologies? Currently, the evaluation of multi-decadal variability seems visual, making it difficult to assess.

We will replace 'multidecadal' with 'change in temperature trend'. The changes we see are too long relative to the temperature time series for spectral analysis.

406-408: It's difficult to assess the changes in the NE vs. SE Indian Ocean zonal gradient given that the spatial domains used to calculate the gradients were not provided. It's unclear to me whether the authors took averages of the entire northern and southern Indian ocean, or focused specifically on the NE and SE Indian Ocean.

The spatial domains were listed in the caption of Figure 9. We will add them as rectangles in Figure 2. We followed Weller et al., 2014, and focused on the NE and SE Indian Ocean.

409: Here, you suggest that your results indicate a warmer eastern Indian Ocean relative to the western Indian Ocean, but in lines 403-405 you said that your data suggest that the western Indian Ocean is warming faster than the eastern Indian Ocean. The positive values in the west-east gradient in Figure 9 from the 1980s-2000s would suggest that the western Indian Ocean is warmer than the eastern Indian Ocean. Is there a specific time period you are focused on that you can discuss more clearly?

The sentence refers to the time period before 1925. At the time, the eastern Indian Ocean was warmer than the west. We will re-write this sentence for clarity.

410-411: It only seems possible to have a stronger north-south meridional SST gradient in the east in the earliest portion of the record (1970-1910). Is this the time period you mean to discuss? Make sure to be specific in the main text to clarify at which time periods each process is occurring. It would also be helpful to add a comparison of the Lenssen et al. (2019) results to Figure 9 to compare with your findings and support your conclusions.

We will clarify the time period (1870-1917). Results with GISS are fully consistent, and do not add to our story. In the revised manuscript, we will compare the modern corals with the HaCRUT5 temperature gradient.

428-434: I'm still unclear how the results presented in this manuscript indicate a shift in the ITCZ. The ITCZ migrates to the northern hemisphere seasonally. Are you specifically discussing the southern margin of the ITCZ?

Yes, and we will clarify this.

442: Enggano is located at 5ºS, so it is not south of 7ºS latitudes.

We meant to say that the SST variability we see at Enggano Island between 1917 and 1855 is comparable to the SST variability seen today at 7°S. We will clarify this.

459: Do you mean between 1823 and 1854 as is indicated in Figure 7? Make sure you are consistent in your time periods across all figures and text.

Thank you, we mean 1823.

464: change to "linked"

Thank you.

475: It would be helpful to add a panel to this figure where you examine the change in SST gradient between the Mentawai and Enggano coral records to support the discussion in Section 5.5

This would indeed be very interesting, but according to Abram et al. (2008) the Mentawai record includes SST and d18Oseawater/rainfall. We would prefer to use a coral Sr/Ca record for this. Maybe this will become available in the future.

476: 10-year running averages are not shown in panel a

Thank you, we will correct the figure caption.