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Nerilie Abram,
Editor
Climate of the Past

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

Dear Editor,

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

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

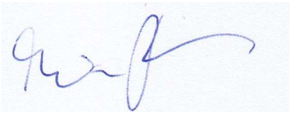
2. We will replace 'Intertropical Convergence Zone' with 'Tropical convergence Zone' (TCZ) following Reviewer 2 and clarify that we focus on northward shifts of the southern margin of the TCZ in austral spring (September-November).

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

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

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.

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.

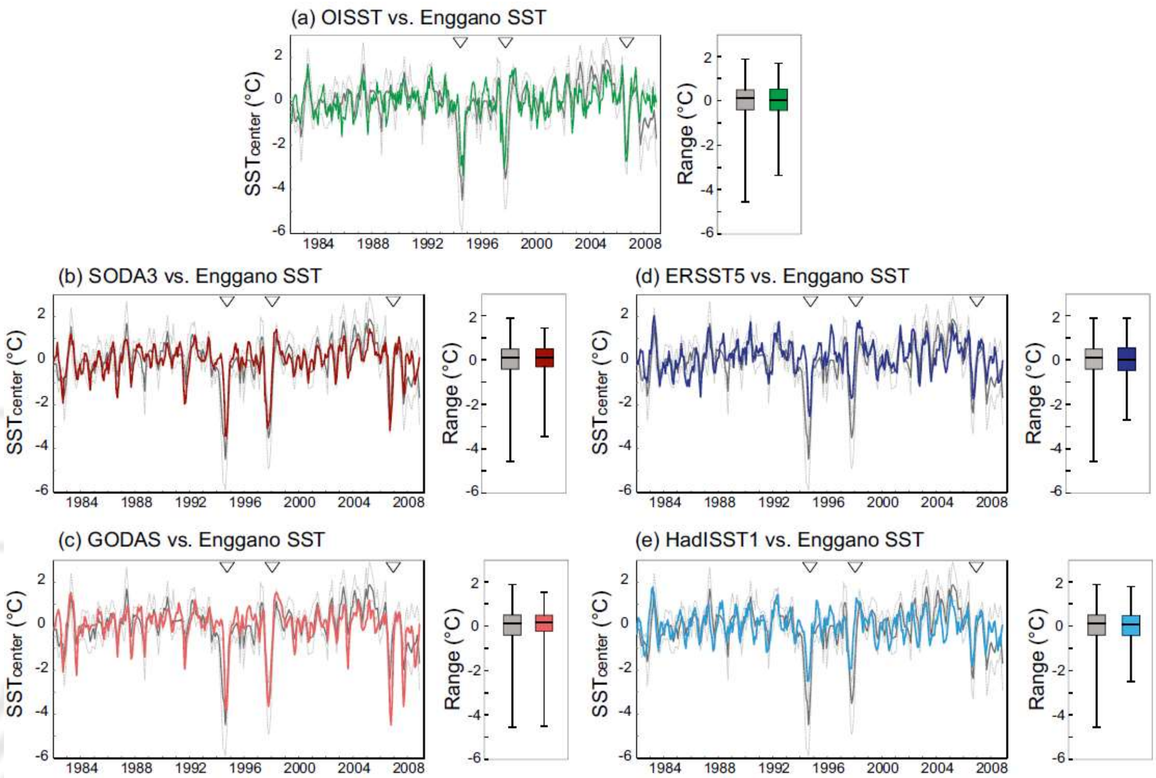


Figure 3. Monthly instrumental SSTs from various products and their SST range (boxplots showing median, interquartile range and maxima/minima as whiskers) compared with the monthly Enggano SST record (in grey) for the time period of 1982–2008. (**a**) OISST (green), (**b**) SODA3 SST (dark red), (**c**) 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.