Point-to-point reply to Reviewer #1 comments by Leupold et al.

We are grateful for the feedback provided by an anonymous reviewer. The reviewer raises seventeen (RC1 –1 to RC1 – 17) specific comments, which are addressed in detail below. Additionally, technical corrections are provided by the reviewer, which are addressed below, as well. In the following, we will repeat the reviewer's statements (in bold font) and our reply to it. Below the responses to these specific comments, we respond to the technical corrections. Numbers in brackets at the beginning of our comments indicate line numbers of the revised version of the manuscript with highlighted changes.

Specific comments

RC1 - 1

- l104: "ENSO Indices" There is in my opinion more recent ENSO time series that you coul have. Why did you chose to use only "old" reconstructions?

(l. 122) We wanted to use as few indices as possible, and the same indices for all coral time windows shown in our study, for consistency. However, we did not only rely on the Quinn record from 1993. We compared Quinn 1993 with the list of ENSO events compiled in Brönnimann et al., 2007 (https://doi.org/10.1007/s00382-006-0175-z). We believe that this gives some indication of the sensitivity of our results with respect to different ENSO reconstructions. Both records cover all our coral time windows, including our 17th century coral record. Brönnimann et al. (2007) combined several reconstructed ENSO indices (ERSST NINO3 by Smith and Reynolds, 2004 (https://doi.org/10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2); Mann NINO3 by Mann et al., 2000 (https://doi.org/10.1175/1087-3562(2000)004<0001:GTPIPC>2.3.CO;2); Cook/D'Arrigo NINO3 by Cook, 2000 (https://www.ncdc.noaa.gov/paleo-search/study/6250) and D'Arrigo et al., 2005 (https://doi.org/10.1029/2004GL022055); Stahle SOI by Stahle et al., 1998 (https://doi.org/10.1175/1520-0477(1998)079<2137:EDROTS>2.0.CO;2)), climate field reconstructions and early instrumental data and also assessed the data for consistency.

RC1 - 2

- **l137: "concentration of approximately 8ppm Calcium". I'm a bit surprised by this value. Usually with 0.6 mg of carbonate powder in 6mL you are getting 50ppm of Calcium. Additionally, Villiers et al. (2002) that you are citing above recommend analyzing between 40 to 60 ppm of Ca.**

(l. 166) We do not dilute 0.6 mg of carbonate powder in 6mL. In a first step, we dilute the powder in 1.00 mL 0.2 M HNO_3. In a second step, we take a specified volume from this solution and add 0.2 M HNO3 to get a final concentration of approximately 8ppm Calcium in 6mL.

The concentration of Ca in the measuring solution is determined by the concentration of the trace element to be analyzed:

For Mg (Mg/Ca) in foraminifers which is the target analyte of the de Villiers et al. (2002) and Schrag (1999) papers we use Ca at 40-50 mg/L giving best response of the Mg 279 line in our instrument at given conditions.

For Sr (Sr/Ca) in corals we use the Sr-407 emission line with very high sensitivity in our instrument so that we had to reduce the Ca concentration to 8 mg/L. This also allows for reduced sample weights and, therefore, for higher time resolution in the coral.

It is the concentration and response of the trace element that defines the required concentrations in solution for getting best counting statistics. The Ca concentrations are, as a consequence, determined by the trace element response and the Mg/Ca and Sr/Ca ratio of the sample, and not vice versa.

RC1 - 3

- l140: Can you, please, indicate why you did not use any CRM such as JCp-1? Can you, please, be more specific and give the mean % of recovery ± SD and the N values

(l. 169) In total, 5 different CRM were used, including the international CRM JCp-1 and JCt-1. They were measured before and after each measurement sequence. We explained this in more detail in the methods section in the revised version. Furthermore, we added error bars on all coral Sr/Ca plots and added precision values in the methods section.

RC1 - 4

- **l149: "We assigned the highest Sr/Ca value to the SST minimum of each year and interpolated linearly between these anchor points to obtain a time series with equidistant time steps" Which software did you use? Why only interpolate between two consecutive high values? Why not between two lows or between one high and one low as it is usually the case?**

(l. 187) We developed the age model following the pioneering work of Charles et al., 1997 (https://science.sciencemag.org/content/277/5328/925), who has proposed to use the month of August as one single anchor point in any given year at the Seychelles, a site located slightly further west than Chagos with a similar monsoon-dominated SST seasonality. Charles et al. have demonstrated that with their approach, monthly anomalies can be computed from coral proxy data, and that these monthly anomalies can be correlated (calibrated, in fact) with instrumental SST anomalies. See Charles et al., 1997, Figure 2 B.

Due to the strong cooling of the western and central Indian Ocean following the onset of the Indian summer monsoon in boreal summer, which is seasonally phase-locked, this age model is very precise (the non-cumulative age model error is +/-1 month in any given year). Each additional anchor point would introduce an additional error which, in the Indian Ocean, tends to be larger during the other seasons of the year.

Using only the lows would also introduce a larger error, as the austral summer warm season is longer and more variable then the monsoon-induced cool season.

RC1 - 5

- **l193: I would have liked to see how you determine the annual mean (average between two max Sr/Ca) ? and how did you determine the standard error?**

(l. 228) The annual means were generated by averaging every value of one year (Jan-Dec). When averaging different values, you can determine a standard deviation for this calculation, what we did with Excel. With the standard deviation, we calculated the standard error with the formula below.

The standard error (SE) were used and calculated as follows:

SE = (standard deviation (σ))/$\sqrt{}$ (Number of values (n))

RC1 - 6

- **l218: Can you please explain how and especially why you decided to detrend the record?**

For detrending we used published methods by Mudelsee, 2000 (https://doi.org/10.1016/s0098-3004(99)00141-7) and Mudelsee, 2009 (https://doi.org/10.1140/epjst/e2009-01089-3). As it can be seen in figure S7 in the revised Supplementary Material, the long-term trend was subtracted and not, e.g., the annual cycle. Detrending was necessary for time series analysis (singular spectrum and power spectrum analysis) and to compile the composite records. With the long-term trend being subtracted out, the anomaly events could be detected (see also figure S7).

RC1 - 7

- **l223: You should not cite Figure 7-9 while talking about ENSO event frequency, those figures are not at all giving information on frequencies.**

(l. 269) We agree, that figures 7-9 do not say anything about ENSO frequency. We revised this paragraph to shorten the interpretation on ENSO frequency and to make our focus more central.

RC1 - 8

- **l228: I'm confused l226 you indicate that El Nino events occurs every 5 years between 1965 and 1995 and l228 you mention a recurrence time of 3.6 years ...**

We agree that this might lead to confusion. The recurrence time of 3.6 years between 1965-1995 mentioned in l228 is taken from the list of events in Quinn 1993 (as mention one sentence before in l227). We wanted to compare the recurrence times calculated from our coral records with that calculated from published data. However, we revised this paragraph anyway as we shortened the sections on the time series analysis, as these were only used to show that ENSO periodicity is observed in the coral records and may distract the reader from our main results.

RC1 - 9

- **l229: Can you please indicate here which threshold you used when considering an anomaly and therefore considering that it is an El Nino or La Nina year?**

The events described in this paragraph are the same listed in Tables 4, 5 and 6. They were picked as described in section 4.5 in the manuscript: "…Positive SST anomalies in the coral records were interpreted as positive ENSO events when the year of occurrence was listed as one with large-scale ENSO event in Quinn (1993) and Brönnimann et al. (2007) within the error of each coral age model and **when the anomaly exceeds 1.5 standard deviations of the mean of each coral record** (Fig. S7 of the revised supplementary material). In addition to the strong La Niña events listed in Brönnimann et al. (2007), we added negative SST anomalies occurring in years after the El Niño years to the composite."

RC1 - 10

- **l240: Using data from Quinn (1993). I do believe that there is more up to date studies on ENSO events... I would feel more confident in your results if you had compared to multiple studies.**

(l. 283) As also mentioned in l240, we not only used data from Quinn (1993), but also from Brönnimann et al., 2007 (https://doi.org/10.1007/s00382-006-0175-z), who provides a synthesis of multiple ENSO reconstructions. For an extended explanation why we used these lists/indices, see our comment below reviewer comment RC1 - 1 in this document.

RC1 - 11

- **l241: "error of each coral age model". What values did you use as a bracket for the age model uncertainty?**

(l. 289) As mentioned in section 3.3 Chronology (in l152 of the initially submitted manuscript; in l. 177 of the revised version), the uncertainties of the age models are approximately ±1.9 years (E5), ±2.2 years (B8) and ±2.4 years (E3).

RC1 - 12

- **l242: "we added negative SST anomalies occurring in years after the El Niño years to the composite." I do not understand - are those considered La Niña-like events?**

(l. 290) As La Niña events tend to occur after El Niño events, e.g. Cai et al., 2015 (https://doi.org/10.1038/nclimate2492), we interpreted negative anomaly events exceeding 1.5 standard deviations of the mean of each coral record (Fig. S7 of the revised supplementary material) and occurring after El Niño events as La Niña events.

RC1 - 13

- **l266: "the greater sensitivity of the corals to reef-scale". Can it reflect also issues with the calibration you used to convert Sr/Ca to SST?**

(l. 314) A detailed calibration for modern corals from the same site (Chagos Archipelago) was presented in Leupold et al., 2019 (https://doi.org/10.1029/2018GC007796). In this study, the regression of coral Sr/Ca with satellite data indicates a significant correlation (r-squared: 0.62, p<<0.01, n=265). As we used the slope of this regression in our study, it probably does not reflect issues with the calibration we used to convert Sr/Ca to SST.

RC1 - 14

- **l301-032: "However, … "Something is wrong with this sentence. How could differences between means are not significantly different with one p value of 0.9 and one of 0.07 .... Additionally, does that mean that the decrease in amplitude of the negative anomalies are not statistically significative?**

(l. 349) In most fields of scientific work, it is common to apply a confidence level of 99%. In this case, the corresponding significance level is 0.01. Both p values (0.9 and 0.07) are larger than our significance level of 0.01, i.e. they show that the difference between the means is not statistically significant. So, yes, this means that the decrease in amplitude of the negative anomalies between the period 1830-1929 and the period 1965-1995 is not statistically significant.

RC1 - 15

- **l322-323: Can you please develop a bit more on this idea.**

(l. 383) In this paragraph, we described larger anomaly amplitudes during a period of general cooler mean temperatures, which is consistent with results shown in Pfeiffer et al., 2017 (https://doi.org/10.1038/s41598-017-14352-6) and Zinke et al. 2004 (https://doi.org/10.1016/j.epsl.2004.09.028). We are not sure why this is the case. However, the tropical Indian Ocean is the warmest tropical Ocean, and recent instrumental data suggests that, as the Indian Ocean continues to warm, the temperature variability reduces particularly in the warm season, while SSTs in the cold season show strongest warming (e.g. Leupold et al., 2019 (https://doi.org/10.1029/2018GC007796); Roxy et al., 2014 (https://doi.org/10.1175/JCLI-D-14-00471.1)) and largest spatial variability (Leupold et al, 2019 (https://doi.org/10.1029/2018GC007796)).

RC1 - 16

- **l325: "comparable". Comparable to what? You also need to be consistent, you have been using the term "coral composite" and know you are using "Chacos coral"... it is a bit confusing, we are wondering if you are not referring to something else ...**

(l. 360) With this sentence we want to say that El Niño magnitudes are comparable to La Niña magnitudes. We used Chagos coral records in this sentence, because the El Niño and La Niña events are recorded in the corals from Chagos, they are not recorded in the "Composites". The composites were then generated by selecting the El Niño and La Niña event anomalies recorded in the Chagos corals.

RC1 - 17

- **l344: You mean the frequency because the strength of the events are different, there is no change in strength of ENSO events in your study during the 20th century (Figure 9).**

We are not sure what the reviewer wants to point at with this comment, because in l344 we did not write anything about the strength of events.

Technical corrections

You need to change all the reference of the Supplementary figures as they are wrongly numbered in the text

We did not find that they were wrongly numbered. However, as the other reviewer also mentioned wrong numbering of the supplementary figures, we changed the titles of each chapter in the supplementary material which may have caused the misunderstanding. In the originally submitted version, e.g. chapter 3 of the supplementary material was named ‘S3 X-ray images’ that included ‘Figure S2’. After revision, this chapter’s title is now ‘3 X-ray images’.

You need to change the numbering of the Supplementary Figures legends.
Revised.

You need to cite Figure S1 in the text
Figure S1 was already cited in the originally submitted manuscript (as ‘Fig. S1’ in line 118).

- l37 : “There are only some studies including Sr/Ca measurements for SST reconstructions (e.g. Pfeiffer et al., 2006), while few studies included Sr/Ca measurements for SST reconstructions (e.g. Pfeiffer et al., 2006).”There is a problem with this sentence. You wrote twice the same idea.
(l. 37) Thank you for pointing this out. We revised this sentence.

- l39: “Most studies are focusing on either the western or the eastern Indian Ocean (Abram et al., 2003; Watanabe et al., 2019) and/or are sampled at only bimonthly … “ Be careful it is not the study that are sampled at bi monthly resolution but the coral.
(l. 37) We revised this sentence.

- l51: “The modern core was included in a composite reconstruction of large-scale SST (Pfeiffer et al., 2017) and the core top (1950-1995) was shown to record SST variability at Chagos on grid-SST scale (Pfeiffer et al., 2009).” I'm a bit confused by sentence. Maybe should explain a bit more what you had in mind while writing it. One core records more global scale SST variability while the other more the local variability? Is that it?
(l. 66) We simply wanted to say that core GIM has been calibrated with SST in a previous study. In addition, it has been part of a composite coral record for the western equatorial Indian Ocean (together with corals from the Seychelles). We revised this paragraph.

- **l53: “41 years of the Maunder” Can you write instead “41 years during the Maunder**
(l. 65) We adjusted this sentence but exchanged “Maunder Minimum” with “period of the Little Ice Age”, as we used the term Maunder Minimum in a misleading/incorrect way.

- l54: “39 years of the mid-19th to early 20th century (1870-1909) covering 39 years”. You wrote twice the same info about 39 years.
We shortened this paragraph.

- **l55: “We identify past warm and cold events in each record and use these events to compile composites to evaluate the symmetry of positive and negative ENSO-driven SST anomaly events in the tropical Indian Ocean.” This paragraph seems out of context here.**
(l. 70) With this sentence we explain what we will focus on in this study. We think, it is essential to have it in the introduction. However, we added more text on ENSO asymmetry in the introduction of a revised version of our manuscript and revised this sentence to better convey the main aims of our study.

- **l62: “… water exchange with the open ocean is substantial.” Do you specify that because your coral core is from inside the lagoon?**

(l. 80) We specified it to give a better idea of the setting. We do not know where the coral lived exactly as they were found as boulders at the beach or in derelict buildings.

- **l98: "Averaged over the entire area of the Chagos (70-74° E; 4-8° S), SST is similar…" It would be interesting to add the mean values for both sites.**

(l. 114) We added the mean SST for both sites in the revised version. We do not interpret the mean values of our Sr/Ca data. In corals, these are influenced by vital effects, see e.g. Sayani et al., 2019 (https://doi.org/10.1029/2019GC008420).

- **l104: "ENSO Indices" You might want to introduce this paragraph as the time series you will compare your records to? Or something in this line.**

(l. 122) We agree, we added a sentence stating that the indices presented here are the ones we use for comparison with our coral data.

- **l125: "The core top (1950-1995) was shown to record SST variability at Chagos on a grid-SST scale (Pfeiffer et al., 2009). The entire record was included in a composite reconstruction of large-scale western Indian Ocean SST (Pfeiffer et al., 2017)." Those sentences are similar to the ones l51 that I did not understand. The top core was comapred to grid-SST data and it maches perfectly and then the entire record was used in a coral composite but with which other corals? Can you, please, add more information here.**

(l. 155) The GIM core was included in the coral composite of the Seychelles-Chagos thermocline ridge. This composite comprises cores from the Seychelles and Chagos. We added this information in the revised version.

- **l128: "From the slabs of the sub-fossil corals, powder samples were drilled at 1 mm increments using a micro-milling machine (type PROXXON FF 500 CNC). This depth resolution can be translated to monthly temporal resolution with average growth rates being 12 mm/yr. The subsampling paths were always set along the optimal growth axis that was determined based on x-ray images (Fig. S2)." Can you please add some information on the sampling over laps that you had to do when switching sampling paths? How did you determine the temporal resolution, by looking at the density band or by looking at the seasonal cycles in Sr/Ca data? You might want to move this paragraph up right below where you talk about your new coral core samples.**

(l. 151) All sampling paths were selected so that we get a continuous record for each coral sample. This includes, e.g., both sampling paths on coral slab E3. For this sample, there is an overlap of 10 mm, which means 10 subsamples, for each sampling path, i.e. there is around one year of overlap. We determined the temporal resolution by combining the interpretation of the annual bands visible in the x-rays and the seasonal cycles recorded in the Sr/Ca data.
We moved this paragraph below the paragraph in which we talk about our new coral core samples. In the revised version of this manuscript (in the supplementary material), we show the raw Sr/Ca data, including the overlaps, as requested by reviewer 2.

- **l138: "The intensities of Strontium and Calcium were converted into Sr/Ca ratios in mmol/mol." Which method did you use to convert the instrument output in intensity to concentration values 1) the calibration given to you by the instrument? or 2) the deVillier et al., 2002 ratio method?**

(l. 168) We converted the intensities of Sr and Ca into Sr/Ca ratios following the methodology proposed by deVillier et al., 2002.

- **l165: Statistic Section : I would like to see this section a bit above as you use statistics in above paragraphs**

(l. 198) We do not see why we should put the statistic section above the other sections in the methods section, because it only introduces statistics used and described in the results and discussion part of the manuscript.

- **l166: "Composite were generated calculating…" replace by "Composite were generated by calculating…"**

(l. 205) Done.

- **l175: Can you please indicate in which occasion you use the t-test**

(l. 209) T-tests were used to determine if the mean values of two data sets, e.g. mean annual cycles in chapter 4.3 or mean values of coral composites in chapter 4.5, are significantly different from each other. We added this sentence to the corresponding paragraph in the manuscript.

- **l188: It would be interesting to have at the end of the Diagenesis section a summary sentence stating that your sampled should all be good for geochemical analysis and that the results should not be impacted by secondary calcification ...**

(l. 224) Done.

- **l189: In my opinion you do not need subsections, but instead a big paragraph labelled Sr/Ca data description, where you describe the results core by core**

(l. 226) We think that subsections give a better overview as we have coral samples from different time windows.

- **l192: Porites needs to be in italic**

(l. 200) Done.

- **l196: "The range …" Is that the mean range or the maximum range?**

(l. 231) It is the range between the maximum and minimum Sr/Ca value (see also table 2). We added the word "maximum".

- **l206: Can you please describe how you determine the mean annual cycle?**

(l. 240) The mean annual cycles were calculated by averaging interpolated Sr/Ca values for every month over the given time period covered by each coral record. For example, B8 covers 31 years from 1836-1867. For this period, all Sr/Ca values for January were averaged, all Sr/Ca values for February were averaged, all Sr/Ca values for March were averaged, and so on.

- **l207: "The seasonal amplitudes in coral SST [°C] are slightly higher" You should be using parenthesis instead of brackets**

(l. 248) Done.

- **l209: I do believe you should spend a little more time describing Figure 4.**

(l. 241-246) We added a more detailed description of Figure 4 in section 4.3. in the revised version.

- **l224: “Our results show that,…” I'm guessing that these conclusions derived from Table 4-6: you might want to refer to it as well as indicate some stats about this change of frequency. Maybe the percentage of increased frequency?**

(l. 269) Yes, these conclusions derived from Tables 4-6. We indicated this with an introducing sentence that included the reference to Tables 4-6 at the beginning of the paragraph. However, we included it once again at the end of the follow-up sentence. Furthermore, we revised this paragraph anyway as we shortened the sections on the time series analysis.

- **l225: Replace the “:” by “.”**

(l. 271) Done.

- **l226: Remove here also the reference to Figure 7-9.**

(l. 273) Done.

- **l241: “referring to Figure S6”. Figure S6 correspond to the detcoral Sr/Ca records after detrending. Which Figure are you referring to here?**

(l. 290) We are referring to Figure S6 (now Figure S7 in the revised version of the supplementary material). In the lower plot, 1.5x of the standard deviation is plotted as dashed lines. Peaks above this standard deviation were considered as anomaly events when listed in Quinn (1993) or Brönnimann et al. (2007). Detrending was necessary for compiling the composite records. With the long-term trend being subtracted out, the anomaly events could be detected. That is why we indicated the standard deviation in this figure and that is why we referred to this figure in this paragraph.

- **l245 – 251: This paragraph should be in the method section.**

(l. 293) We did not put this in the methods section, because it already consists of our interpretation. We interpret the anomaly events to be El Niño and La Niña events. We think, putting this paragraph in the method section would confuse the reader as it requires information which is provided only later in the manuscript.

- **256-258: This sentence has no link with the previous sentence and should be separated from it.**

(l. 305) Done.

- **l259: “we compared”. I do not think "compare" is the right word. You do not compare, you use the same technique to discriminates El Nino from La Nina from negative events other than La Nina years, right?**

(l. 308) That is correct, we also selected the events recorded in the satellite data using the same techniques. But in the end, we compared the results of the satellite data (how many events and the amplitudes) with our coral data.

- **l263: “All SST anomalies were … of -0.06 mmol/mol per 1°C (see Leupold et al., 2019).” This section looks more like a material and method section. You do not talk at all about what you found.**

(l. 199) This paragraph primarily focusses on the anomaly events we interpreted. However, we agree that we should put sentences like this, regarding the calculation of the SST anomalies, in the methods section, which we now did in the revised version of the manuscript.

- **l265: “Coral SST proxy”. What is that? Is it your so-called ENSO composite?**

(l. 313) It is the coral Sr/Ca data, which is used as an SST proxy. We used this expression here, because the ENSO composite is the result of calculations we did with our coral data. We improved the wording in the revision.

- **l265: "Ocean record similar, but higher anomalies". If it is higher it is not similar. What do you mean by "similar"?**

(l. 313) We deleted "similar".

- **l269-271: Those two paragraphs talk about the same subject; you should not separate them.**

(l. 317) Revised.

- **l274: "from those". You mean from the coral composite, right? It is not clear; you might want to rephrase.**

(l. 322) Revised.

- **l288: "On average … (p=0,75)". This sentence is a bit similar to the first sentence of the paragraph, no? You might want to regroup them.**

(l. 329) Thank you for pointing that out. We adjusted it in a revised version.

- **l293: You forgot the "." at the end of the sentence.**

(l. 341) Added.

- **l298: You need to regroup this sentence with the next paragraph as they discuss the same idea.**

(l. 329) Done.

- **Figure S1 : Can you please add an arrow to actually point at the boulder you sampled? Can you please add a symbol of the lagoon of Peros Banhos site location on your Map**

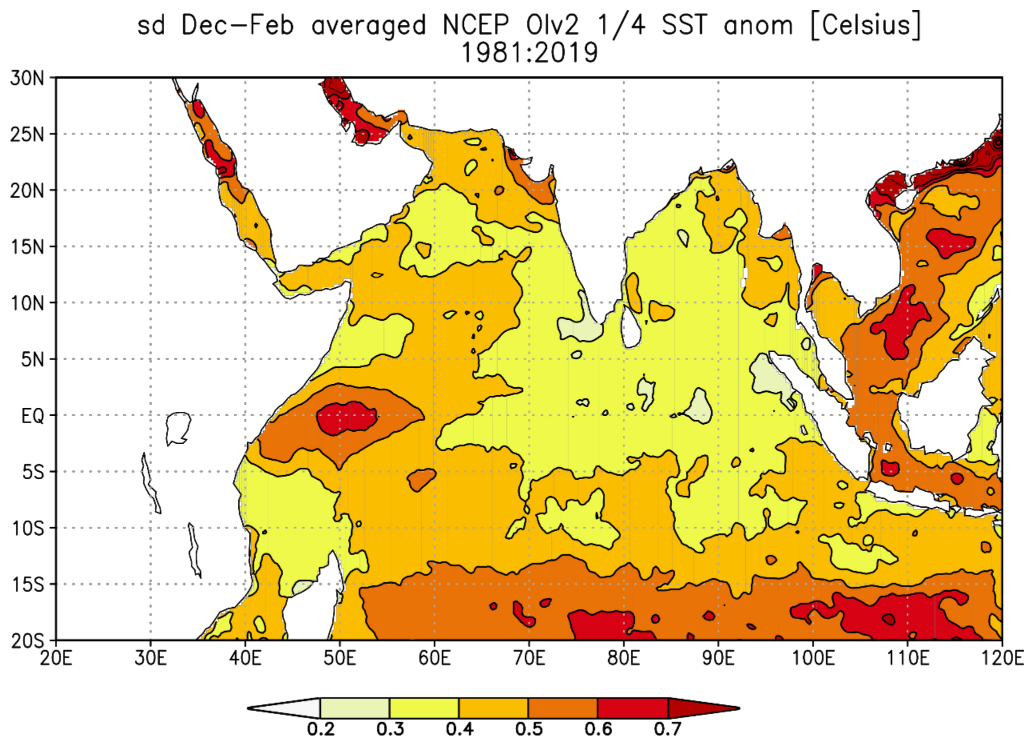
We added arrows marking E3 and E5 in the revised version of the supplementary material. In figure 1 (location of our study area) of the main manuscript, the lagoon of Peros Banhos is already labeled.

Point-to-point reply to Reviewer #2 comments by Leupold et al.

We are grateful for the feedback provided by an anonymous reviewer. The reviewer raises fourteen (RC2 –1 to RC2 – 14) specific comments, which are addressed in detail below. Additionally, technical corrections are provided by the reviewer, which are addressed below, as well. Furthermore, additional comments to individual points of the manuscript are provided in an annotated pdf. In the following, we will repeat the reviewer's statements (in bold font) and our reply to it. Below the responses to these specific comments, we respond to the technical corrections and to the additional comments on the manuscript. Numbers in brackets at the beginning of our comments indicate line numbers of the revised version of the manuscript with highlighted changes.

General Remarks to the comments of Reviewer #2:

Reviewer 2 has problems with understanding our concept of ENSO asymmetry, which **does not refer to the question whether there are more El Niños than La Niñas**, but their **magnitude in terms of SST anomalies** in the Indian Ocean. A quote from the abstract of our original manuscript (Line 17-19): 'El Niño events have occurred more frequently during recent decades **and** it has been suggested that **an asymmetric ENSO teleconnection (warming during El Niño events is larger than cooling during La Niña events)** caused the pronounced warming of the western Indian Ocean.' We agree that our manuscript requires an unambiguous definition of ENSO asymmetry in the central Indian Ocean and we will provide this in the introduction of a revised version of our manuscript.
We do not aim to reconstruct ENSO frequency with the central Indian Ocean corals, as done in numerous studies with corals from the tropical Pacific (cited as examples by Reviewer 2), where ENSO dominates and causes large SST anomalies that can be unequivocally identified in coral proxy data. ENSO (and IOD)-induced SST anomalies are small in the Indian Ocean (~0.5-0.7°C, see Figure 2 of our manuscript and Roxy et al., 2014; (https://doi.org/10.1175/JCLI-D-14-00471.1)) relative to the background variability (~0.3-0.4°C in the peak ENSO season from December-February; see Figure below) and their identification requires a reference record of past ENSO events. We are aware of the excellent coral reconstructions from the tropical Pacific that record past ENSO events that would be ideal for this purpose.



Map of the Indian Ocean with standard deviation (in °C) of SST anomalies from Dezember to February averaged over the time period 1981-2019.

However, to date all these reconstructions are restricted to certain time windows and do not cover the entire time intervals of our central Indian Ocean corals. We therefore used the classical list of ENSO events from Quinn alongside with the updated list of Brönnimann et al., 2007 (https://doi.org/10.1007/s00382-006-0175-z), who evaluated and synthesized a number of ENSO reconstructions (ERSST NINO3 by Smith and Reynolds, 2004 (https://doi.org/10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2); Mann NINO3 by Mann et al., 2000 (https://doi.org/10.1175/1087-3562(2000)004<0001:GTPIPC>2.3.CO;2); Cook/D'Arrigo NINO3 by Cook, 2000 (https://www.ncdc.noaa.gov/paleo-search/study/6250) and D'Arrigo et al., 2005 (https://doi.org/10.1029/2004GL022055); Stahle SOI by Stahle et al., 1998 (https://doi.org/10.1175/1520-0477(1998)079<2137:EDROTS>2.0.CO;2); Quinn and Neal, 1992 (Quinn, W., & Neal, V., 1992: The historical record of El Niño events. Climate Since AD 1500: 623–48. R. Bradley and P. Jones.)). So, our interpretation does not rely on an outdated version of ENSO events. Rather, by including the original list of Quinn, we aim to evaluate the sensitivity of our analysis to different ENSO reconstructions.

The excellent coral IOD reconstruction of Abram et al. (2020) was published after the submission of our manuscript. However, Abram et al. (2020) demonstrate the tight coupling between the IOD and ENSO during the past millennium, lending confidence to our approach.

Anonymous Reviewer #2

Specific comments:

RC2 - 1

While this study is addressing an important question and producing valuable coral SST reconstructions for a location with few such records, this reviewer finds they do not address the research question posed for their study, were there more El Nino events than la Nina in a robust manner. They do look at magnitudes of these events but not the "asymmetry" they discuss in the introduction or that as suggested by Roxy et al. 2014. This should be a straight forward analysis to test this question but the authors use a wide variety of software programs and several data analysis methods to try and address this question that leads to confusion and as a whole, misses the point of their analysis. For example, they spend considerable time and present several figures with spectral analysis that look for periodicities/frequencies in their data. Since El Nino and La Nina are opposites phases of the ENSO variability or "periodicity" they are looking for, the spectral analysis tells you nothing about whether or not more El Ninos occurred than La Ninas.

The term 'ENSO asymmetry' is based on the conceptual work of Burgers and Stevenson ('The Normality of ENSO', 1999, GRL, vol 8) and An and Fin ('Nonlinearity and Asymmetry of ENSO', 2004, Journal of Climate, https://doi.org/10.1175/1520-0442(2004)017<2399:NAAOE>2.0.CO;2). ENSO asymmetry refers to the fact that El Niño events are often stronger than La Niña events, as seen in the tropical Pacific. This does not always apply to teleconnected sites. For example, Brönninam et al. (2007) find that 'the responses to El Niño and La Niña are close to symmetric' in Europe during winter and spring.

In the abstract of our original manuscript, we state that: 'El Niño events have occurred more frequently during recent decades **and** it has been suggested that **an asymmetric ENSO teleconnection (warming during El Niño events is larger than cooling during La Niña events)** caused the pronounced warming of the western Indian Ocean.' (Line 17-19)

Based on the comments of reviewer 2, we assume that he believes we aim to address the question **whether or not more El Niños occurred than La Niñas. This is not the point addressed in our manuscript.** We do not want to focus on the frequency of past EN/LN events or to address the question whether or not more El Niño than La Niña events occurred in the central Indian Ocean. The question we address is: do El Niño events warm the Indian Ocean more than La Niña events cool it. However, we agree that the main aim of our study should be expressed more clearly. In the revised version of the manuscript, we try to clarify these points and define what is meant by asymmetric

ENSO teleconnection and how we use this term in our study. We also shortened the sections on the time series analysis, as these were only used to show that ENSO periodicity is observed in the coral records and may distract the reader from our main results. In the main manuscript, we now only show the wavelet coherency plots (Figure 6), as these show the correlation between our coral Sr/Ca records with ENSO as a function of frequency over time.

RC2 - 2

Spectral analysis is suggestive of periodicities similar to ENSO but is NOT conclusive evidence, see Hochman et al. 2019 (doi: 10.1175/jamc-d-18-0331.1) and Liu et al 2007 (doi: 10.1175/2007jtecho511.1). A large anomaly with the width of 2-7 years can be manifested as a significant 2-7 year periodicity in a spectrum leading to the misinterpretation of ENSO periodicity (try for yourself, do a FFT spectrum and wavelet spectrum of the volcanic explosivity index and compare).

We used different approaches to test if ENSO frequencies are present in the coral time series: Power Spectrum, Singular Spectrum and Wavelet Coherence Analysis. While the power spectra do not provide conclusive evidence of ENSO, the Wavelet Coherence Analysis does: it shows that there is a positive correlation between an ENSO index (we used the Nino3.4 from Wilson et al. 2010; see discussion further below) and the coral time series at interannual periodicities. However, we realize that this analysis is actually more important than the Power Spectra, and exchanged the figure 6 with figure S11 (wavelet coherence analysis).

RC2 - 3

Furthermore, why do breakpoint detrending, removing monthly anomalies, etc. it is not necessary to answer your question.

For detrending we used published methods by Mudelsee (2000; https://doi.org/10.1016/s0098-3004(99)00141-7) and Mudelsee 2009; https://doi.org/10.1140/epjst/e2009-01089-3). Detrending was necessary to compile the composite records. We then also used this detrended data for the power spectrum analysis. Removing monthly anomalies is a standard procedure to investigate interannual variability.

RC2 - 4

Additionally, using one-tie point per year to build the coral chronology introduces a large amount of uncertainty to your time series, especially in the monthly anomalies that could mask any real signal in time and frequency, see figure 12 of Williams et al. 2014 (http://dx.doi.org/10.1016/j.gca.2014.04.006), and Table 5 in DeLong et al., 2014 (doi:10.1002/2013PA002524). If you are removing the annual cycle from your data, at least two tie points should be used, four is better otherwise your residuals will have a annual cycle still there that introduces spectral noise. There are a considerable number of other studies that look at ENSO variability to ad-dress similar questions.

We developed the age model following the pioneering work of Charles et al., 1997 (https://science.sciencemag.org/content/277/5328/925), who has proposed to use the month of August as one single anchor point in any given year at the Seychelles, a site located slightly further west than Chagos with a similar monsoon-dominated SST seasonality. Charles et al. have demonstrated that with their approach, monthly anomalies can be computed from coral proxy data, and that these monthly anomalies can be correlated (calibrated, in fact) with instrumental SST anomalies. See Charles et al., 1997, Figure 2 B.

Due to the strong cooling of the western and central Indian Ocean following the onset of the Indian summer monsoon in boreal summer, which is seasonally phase-locked, this age model is very precise (the non-cumulative age model error is +/-1 month in any given year). Each additional anchor point would introduce an additional error which, in the Indian Ocean, tends to be larger during the other seasons of the year.

We note that other studies recommended by reviewer 2 as examples also rely on one anchor point per year, e.g. McGregor et al., 2013 (https://doi.org/10.1038/ngeo1936); Hennekam et al., 2018 (https://doi.org/10.1002/2017PA003181).
The approach proposed by the Reviewer (using more anchor points in any given year) would only be applicable at sites that have large-amplitude, sinusoidal seasonal cycles, where age model errors become a problem in the transitional seasons in fall and spring due to the rapid change in SST during a short time period. In fact, the examples cited by the reviewer are from sites with large seasonality, in particular the paper of Williams et al. 2014 (http://dx.doi.org/10.1016/j.gca.2014.04.006), that focuses on red algae from high northern latitudes.
To validate our approach, error estimates based on the standard error where shown in the composites for each mean monthly value.

RC2 - 5

Why "reinvent" the data analysis approach? Just use the methods everyone else uses, band pass filter to remove low frequency variability (> 10year) and trends and higher frequency annual cycle, see collective work of Kim Cobb's lab, (Cobb 2003, 2013, Sayani 2019, Grothe 2019 doi: 10.1029/2019GL083906; Chenet al., 2018 https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2018GL077619,Nurhati et al., 2011 DOI: 10.1175/2011JCLI3852.1) and McGregor 2010 (www.clim-past.net/6/1/2010/) not to mention the excellent work by Hereid et al., 2013(doi:10.1130/g33510.1 and doi: 10.1029/2012PA002352) and the new study published by Lawman et al. 2020 doi: 10.1029/2019PA003742 where they use ENSO variability via histograms and probability density functions to assess ENSO variability in the past that built upon the work of Emile-Geay et al 2016 where they used probability density to assess ENSO variability in a network of coral and mollusks reconstructions and climate models (DOI: 10.1038/NGEO2608). Furthermore, McGregor et al., used a Cluster Analysis to assess El Nino and La Nina amplitudes in fossil corals (DOI:10.1038/NGEO1936) and they use wavelets to band pass filter their coral reconstructions in their 2011 paper (doi:10.1016/j.gca.2011.04.017). The PAST software you are using is capable of doing band pass filters.

We are aware of the excellent work of Kim Cobb's lab and the many other excellent coral-based ENSO reconstructions from the tropical Pacific. For reconstructing ENSO frequency, we agree that the approaches mentioned above are appropriate. However, as mentioned above, reconstructing ENSO frequencies is not our aim and we therefore did not apply any of these methods. Instead we show with our wavelet coherence analysis results that there is a positive correlation between an ENSO index (we used the Nino3.4 from Wilson et al. 2010 (https://doi.org/10.1002/jqs.1297); regarding this index see further below).

RC2 - 6

My second concern is the coral Sr/Ca records in the fossil corals that show large cold anomalies (up to 6◦C?) in Figure 4.The labels in this figure are hard to read but a 4-6◦C anomaly is not expected, even fora La Nina event. The anomaly in Boddam B (1856-1862) spans~6 years and would be manifest in a spectral analysis as a 6-7 periodicity. Look at the Wavelet spectrum for this coral, it will show you if this periodicity is center on this anomaly and this would be why you see 6-7 year peak in Figure 6b. Same could be said for Eagle 3 (1890-1894) and the three year peak. Please include the wavelet spectrum from each series in your paper (better than the spectrums you have and more convincing if not driven by these anomalies).

This anomalously cold peak in Boddam 8 is a relative extreme peak in a phase of generally colder sea surface temperatures. Such decadal variability in the Indian Ocean was already describe in Cole et al., 2000 (https://doi.org/10.1126/science.287.5453), Pfeiffer et al., 2006 and 2009 (https://doi.org/10.1130/g23162a.1; https://doi.org/10.1007/s00531-008-0326-z) and Charles et al., 1997 (https://science.sciencemag.org/content/277/5328/925), and the typical periodicity is 9-13 years. We therefore interpreted this anomaly as one cold event in a decadal cooler phase (note: a 6 year cold interval would not result in a 6-7 year, but in a ~12 year periodicity, as the cold interval would only represent one half of a warm-cold cycle). The extreme peak lasts < 1 year and the absolute

value of this cold event is smaller than 4-6°C: the difference between the cold anomaly event and the minimum peak the year before or the year after this cold peak, respectively, is only 2.6-3.1°C. Large short-term cool events are possible as Chagos lies in a region where open ocean upwelling occurs (see Leupold et al., 2019; https://doi.org/10.1029/2018GC007796).
We agree, however, that this figure is too small to be read properly. We therefore added a larger version of this figure to the revised version of the manuscript.
As mentioned above, we exchanged our power spectrum analysis plots with the wavelet coherence analysis plots (Figure S11). The wavelet coherence analysis was performed with the Nino3.4 from Wilson et al., 2010 (https://doi.org/10.1002/jqs.1297) and shows that there are EN/LN signals recorded in our corals from the central Indian Ocean.

RC2 - 7

Back to the cold anomalies. Looking at the x-radiographs: B8 from(1856-1862) appears fuzzy, could this be dissolution or suboptimal alignment of the corallite to the slab surface (see DeLong 2013 doi:10.1016/j.palaeo.2012.08.019)? If you were to resample this time interval to the far right of that slab, is that cold anomaly still there? I would guess not. Coral E3 has the anomaly from 1890-1894 and this is over the core break in the x-ray image. Do these two paths overlap and how well do they agree with each other? The second path is very close the edge of the coral, could there be local diagenesis there? If you were to sample the second core piece just below the first path, is that cold anomaly still present? For Core Eagle5, the mean shift occurs as the sampling paths shifts from the top to bottom piece of the coral. If you sample a different path with optimal corallites, is this shift still there? All this shifts may be real but any large anomalies should be replicated to see if local diagenesis or suboptimal sampling produce the anomaly. I will note: if you use band-pass filters for your ENSO data analysis, these shifts are less meaningful, but you should make sure your coral Sr/Ca is reflecting the SST signal and not something introduced by sampling. Please include a figure of your raw coral Sr/Ca data with paths in depth in your supplemental materials. Additionally, mark where the XRD and SEM samples were removed from eh slab. It is possible to get pockets of diagenesis in small areas of the coral away from where you did the XRD, thin section, and SEM samples. See Quinn 2006 doi:10.1029/2005GL024972; Sayani 2011 doi:10.1016/j.gca.2011.08.026,Hendy 2007 doi:10.1029/2007PA001462).

The X-ray of Boddam 8 shows traces of saw-cuttings, as the original slab cut in the field was a bit thin for further cutting. We will mention this in the Figure caption of a revised manuscript. This has nothing to do with the preservation of the sample. However, the orientation of the corallites can be seen clearly on the X-ray image. They are always parallel to the slab surface. In fact, the coral shows very even annual growth bands, so irregular growth patterns are not a problem.
All sampling paths were selected so that we get a continuous record for each coral sample. This includes also both sampling paths on coral slab E3. For this sample, there is an overlap of 10 mm, which means 10 subsamples, for each sampling path, i.e. there is around one year of overlap.
The effect of sampling path selection on coral Sr/Ca ratios has been checked systematically in a previous study using modern cores from Chagos (Leupold et al., 2019; https://doi.org/10.1029/2018GC007796; Figure S5 and S6). The reproducibility of Sr/Ca along various sampling paths (in the center and slightly off a major growth axis) is excellent (Figure S5 of Leupold et al., 2019, see below), and while there is some scatter, there is no systematic change of mean Sr/Ca ratios from a major growth axis to the adjacent valley. This may reflect the even growth of the Chagos corals (see Figure S2: E3 and B8 do not show any major growth axis, E5 shows two in the time period from 1890 to 1909, but growth rates are still very similar across the entire sample).

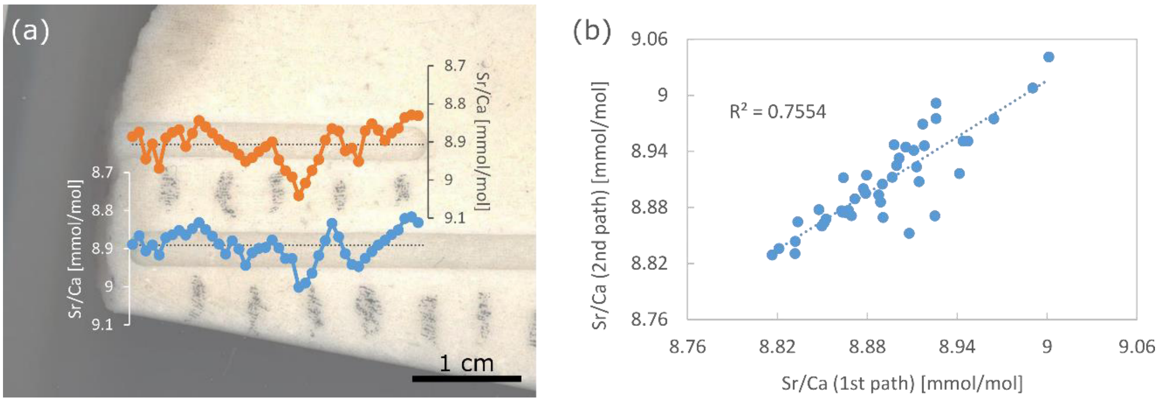


Figure S5. (a) Scan of a modern Chagos coral core top from which subsamples were taken along two parallel sampling paths for Sr/Ca analysis; with results of Sr/Ca analysis (1st sampling path: blue curve; 2nd sampling path: orange curve). (b) Cross plot of both records with regression line (ordinary least squares) and r-squared value indicating a positive correlation. From Leupold et al., 2019.

Regarding possible effects of diageneses: our diagenesis screening revealed that diagenetic modifications to the Sr/Ca record are neglectable. The combination of optical and scanning microscopy and XRD measurements is a well-established method for detecting diagenetic alterations in carbonates by Smodej et al., 2015 (https://doi.org/10.1002/2015GC006009), which has already been applied in several studies, e.g. Deik et al., 2019 (https://doi.org/10.1002/dep2.64), Hallenberger et al., 2019 (https://doi.org/10.1038/s41598-019-54981-7), Pfeiffer et al., 2019 (https://doi.org/10.1029/2019PA003770), Utami & Cahyarini, 2017 (http://journals.itb.ac.id/index.php/jets/article/view/2270), Zinke et al., 2016 (https://doi.org/10.5194/bg-13-5827-2016). The method of Smodej et al. (2015) can identify localized areas of diagenetic calcite and we can therefore also assess potential heterogeneities in preservation. Note that the samples for SEM and XRD measurements were taken from the edges of the coral slab where we expect the 'worst' preservation. From there, also the sub-samples used for U/Th measurements were taken. U/Th is even more sensible to diagenesis than coral Sr/Ca, but our U/Th data shows consistent results with small age errors. We can therefore conclude that even the edges of the coral slabs do not show significant amounts of diagenetic alterations.

We included a figure of our raw Sr/Ca data in the revised vision of the supplementary material (Fig. S2). We also provided better indications where XRD and SEM samples were taken from the coral slabs (Fig. S2).

Please note that decadal-multidecadal temperature variability is common in the tropical Indian Ocean and has been described in numerous studies, e.g. Charles et al., 1997 (https://science.sciencemag.org/content/277/5328/925); Cole et al., 2000 (https://doi.org/10.1126/science.287.5453); Pfeiffer et al., 2009 (https://doi.org/10.1007/s00531-008-0326-z); Hennekam et al., 2018 (https://doi.org/10.1002/2017PA003181). The anomalies seen in our Sr/Ca data are in the range of observed temperature variability at Chagos (Pfeiffer et al., 2009) and there is no reason to suspect that they are artefacts from sampling or diagenesis.

RC2 - 8

The public comments have already questioned the use of the Maunder Minimum in the title and as a climate interval or temporal marker. The paper makes not connections to solar cycles and ENSO variance in the central Indian Ocean and the coral do not span the entire Maunder Minimum so why mention it in the title? I suggest the use of the Little Ice Age in its place, as the records presented are part of this interval and that term is accepted within the climate and paleoclimate literature.

We agree and as already mentioned in our reply to this public comment, we used the term Maunder Minimum in a misleading/incorrect way. We adjusted it in the text and also changed the title of the manuscript. However, we used "…since 1675" instead of "Little Ice Age" as suggested by the reviewer, so that everyone is aware of the exact time interval we are focusing on.

RC2 - 9

The authors need to improve their review of coral Sr/Ca reconstructions in the Indian Ocean. While it is true that there are not many records currently published from the region, there are more than the authors suggest, seven by my count. Line 38-39 if there are few coral Sr/Ca studies, why not list them all to be comprehensive and not just cite the authors own papers. I count 7 studies so is that really a few? Hennekam 2018 doi: 10.1002/2017PA003181 Zinke 2014 doi: 10.1038/ncomms4607 Zinke 2004 doi:10.1016/j.epsl.2004.09.028 Zinke 2008 doi:10.1029/2008GL035634.

In this paragraph, we wanted to point out, that there are only a few coral climate reconstruction studies exist from the central, tropical Indian Ocean (Maldives and Chagos Archipelago) using high-resolution (biweekly to monthly) Sr/Ca records to reconstruct SST. We agree that it is more than the mentioned study by Pfeiffer et al. (2006). We added references for the other studies.

However, we do not count Hennekam et al. (2018; doi: 10.1002/2017PA003181), Zinke et al. (2014 doi: 10.1038/ncomms4607), Zinke et al. (2004, doi:10.1016/j.epsl.2004.09.028) or Zinke et al. (2008 doi:10.1029/2008GL035634) into this category as these studies focused on corals from either the western or eastern Indian Ocean and/or included Sr/Ca of lower resolution. Additionally, from above mentioned Literature, already three studies have been cited in the initially submitted manuscript. However, we missed one study mentioned above. We added this one in the revised version. Besides, we revised this paragraph in general, as parts of it were mentioned twice in the initially submitted manuscript.

Besides, we would like to reject the reproach that we just cite our own papers. Authors of our study, contributed to three studies that we have not cited in the initially submitted manuscript but that were mentioned by the reviewer.

RC2 - 10

The introduction section would also benefit from a more in-depth review of the literature on coral-based SST reconstructions of ENSO, both from the Indian Ocean perspective and also the Pacific Ocean. Lawman et al. (2020) in Paleoceanography and Paleoclimatology, McGregor et al. (2019) in Nature Geosciences, Grothe et al. (2019) in Geophysical Research Letters, and Tangri et al. (2018) in Paleoceanography and Paleoclimatology would all be useful for comparison, and have data available online. These and other ENSO reconstructions can be used for comparisons between basins back to the1600s.

We included a more in-depth review of the literature on coral-based SST reconstructions of ENSO in the introduction of the revised version. We welcome coral data from the Pacific as a baseline for ENSO variability for comparison with the central Indian Ocean data (see Pfeiffer et al., 2009 for a comparison of recent data from Chagos and Palmyra). For the extended time period investigated in this study, the coral data available is still spatially and temporally inhomogeneous, so we preferred to use the classical list of ENSO events from Quinn and the updated list of Brönnimann et al., 2007.

RC2 - 11

I question the authors' decision to count all positive SST anomalies in their coral records as El Niño events, despite the fact that they acknowledge the existence of warm IOD events occurring independently of ENSO (Section 2.2 Climate, lines 92-93).If the authors are comparing other ENSO records to this one, why not remove any positive anomaly events that are unconfirmed by other ENSO records as potential IOD events? Or, why not also compare their record with IOD records? Barring the complete removal of IOD-associated events from the record, I think it would be worthwhile for the authors to compare reconstructions with and without the positive SST anomalies that are not confirmed ENSO events to provide a more complete perspective on potential overestimation of El Niño frequency and strength. I also recommend that the authors review recent literature regarding the IOD, including the recently published Abram et al. (2020) Nature article reconstructing the IOD back to the 13th century AD.

The study by Abram et al. (2020) is indeed a very important one. It states that there are extreme IOD events that occurred independently of ENSO, but also that “a persistent, tight coupling existed between the variability of the IOD and the El Niño/Southern Oscillation during the last millennium.” This supports our approach.

In fact, as it can be seen in Table 6 in the manuscript, all positive anomaly events found in the coral records can be explained with El Niño events listed in either Quinn 1993 or Brönnimann et al., 2007 (https://doi.org/10.1007/s00382-006-0175-z). We just wanted to point out, that there is the possibility, that such events can overlap with IOD events or can even occur independently. Abram et al. (2020) named three extreme IOD events (2019, 1961, 1675) that occurred independently of ENSO. However, both in 1675 and 1961 no positive anomaly events can be found in our records.

Furthermore, the main focus of our study was to study the ENSO teleconnection between the Indian Ocean and Pacific Ocean. Unfortunately, the coral time windows of Abram et al. only partly overlap with our data. In a revised version we mention the IOD events that do not coincide with ENSO events as documented in Abram et al., 2020.

RC2 - 12

In section 2.4, “ENSO Indices”, the authors list the indices that they use for comparison with their coral records. However, they do not discuss whether these records are coherent, or how they vary, over time. It also appears that they generated their own Niño3.4anomaly record, which they call an index. From what I understand, the Niño3.4 index only extends back to 1870, using HadISST, not ERSST. While I applaud the authors for applying their own analysis to the data, it is unclear exactly how they calculated their anomaly record from the ERSST data, and as such they need to describe that process in more detail. Do not call the Wilson ENSO reconstruction Nino3.4, that name has already been taken, just call it Wilson ENSO.

Regarding the introduction of indices, we agree that it might cause confusion as we used two indices named Niño3.4. However, we did not generate our own index. Following the reviewers suggestion, we renamed the Wilson Nino3.4 index. It is now referred to as ‘Wilson Niño Index’. Furthermore, we explained in more detail which index we used to show what in section 2.4.

RC2 - 13

Especially questionable is the application of the Quinn 1993 record (Ortlieb 2000 pro-vides an updated version), which is subjective and based on written records, though I understand the authors are limited in the number of records that they can use due to the limited temporal scope of most ENSO records. I’m particularly confused as to why they did not compare some of their 19th century records to the extended multivariate ENSO index (MEI.ext), which spans 1871-2005 (Wolter and Timlin, 2011), or the more recent series of indices published by Sullivan et al. (2016) that include central, eastern, and mixed-type ENSO events back to 1854? Or any of the other ENSO reconstructions on the NOAA paleoclimate website, there are several to choose from (Cobb 2013, McGregor, 2010, Li 2011, Braganza 2009, Cook 2008, Gergis 2009).

The goal for future coral paleoclimate studies should be to compile a consistent coral data product which overlaps with the entire time period that is studied. However, up to this point there does not exist such a continuous index which overlaps with our records.

We are aware that the Quinn record is based on written records. However, we did not only rely on the Quinn record from 1993. We **compared** Quinn 1993 with the list of ENSO events compiled in Brönnimann et al., 2007 (https://doi.org/10.1007/s00382-006-0175-z). We believe that this gives some indication of the sensitivity of our results with respect to different ENSO reconstructions.

Both records cover all our coral time windows, including our 17th century coral record. We wanted to use as few indices as possible, and the same indices for all coral time windows shown in our study, for consistency. Brönnimann et al. (2007) combined several reconstructed ENSO indices (ERSST NINO3 by Smith and Reynolds, 2004 (https://doi.org/10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2); Mann NINO3 by Mann et al., 2000 (https://doi.org/10.1175/1087-3562(2000)004<0001:GTPIPC>2.3.CO;2); Cook/D’Arrigo NINO3 by Cook, 2000 (https://www.ncdc.noaa.gov/paleo-search/study/6250) and D’Arrigo et al., 2005 (https://doi.org/10.1029/2004GL022055); Stahle SOI by Stahle et al., 1998 (https://doi.org/10.1175/1520-0477(1998)079<2137:EDROTS>2.0.CO;2)), climate field reconstructions and early instrumental data and also assessed the data for consistency.

RC2 - 14

At the very least, a comparison between the two main indices used (earlier than table6/section 4.5) would greatly strengthen the authors' conclusions and help the reader understand their criteria surrounding the selection of El Niño events from these records for comparison. The authors cite Wilson et al. (2010), which analyzes the coherence between several ENSO reconstructions extending back to the 17th century, but do not address the paper's conclusion that inter-reconstruction coherence breaks down in the19th century. Thus, using the Wilson et al. (2010) record to identify individual events in the late 17th – early 19th century seems questionable. Labeling this record Niño3.4was also confusing, making it hard to differentiate between the Wilson record and the ERSST-based anomaly record from the Niño3.4 region. This paper has a lot of potential, but needs extensive work. I commend the authors for attempting an in-depth analysis of their data, but encourage them to consider alternative methods for analysis that would be both simpler to accomplish and ultimately more powerful in their application.

In section 2.4 of the initial submitted manuscript we already introduce all indices we used for this study. However, we agree that we need to provide more detail on which index we used for what so that it does not lead to any confusion. For example, we did not use the index by Wilson et al. (2010) for identifying single ENSO events, as we are aware of the papers conclusion that inter-reconstruction coherence breaks down in the19th century. This is in fact the reason why we decided to use the lists of events from Quinn (1993) and Brönnimann et al., (2007). However, for Wavelet Coherence analysis, we need time series data, and for this purpose, we used the Wilson et al. (2010) record. In a revised version of the manuscript, we placed more emphasis on explaining and comparing the ENSO indices in section 2.4. We shortened the manuscript by omitting unnecessary interpretations on spectral analysis, and table 6/ section 4.5 are more central in the revised version.

Technical corrections:

Figure 6 The authors do not standardize their spectra in time, so that it becomes difficult to interpret the individual plots of Figure 6. Most of the plots are based on monthly resolved data with frequency as cycles/month, except for 6e which is based on annually resolved data and cycles/year and is thus shifted in frequency space.

We did not standardize these plots because they do not have to be compared with each other. Every sub-figure is there to show ENSO periodicities and each resolution is mentioned in the figure caption. However, we decided to exchange this figure with the figure showing the Wavelet Coherence Analysis anyway (see above).

In section 3.1 "Coral collection and preparation" more information about the x-ray system used and the settings applied in the generation of the x-radiographs would be helpful for replication or reproduction by later studies. Are these x-ray positive or negative images? It would also be useful to know how the coral collected from the derelict building arrived there – was it via human activity or storm or tsunami deposited? This is not necessary for publication, but could help guide the location and collection of other specimens.

We provided the additional information about the x-ray system in the revised version of the manuscript.

The derelict buildings were indeed built by humans living on the islands. However, it is not known whether they found their material as boulders on the beach or if they quarried them on the island to get their building material. There are no written records from Chagos from this time. As there can be found hundreds of boulders at the beaches of Chagos nowadays (see Figure S1a) it is likely that the Chagossians first used material they found at the beaches close to their Colony to build their buildings.

This is also suggested by the shape of some of the corals found in the walls, and the ages of the corals obtained by U/Th dating.

In section 3.2 "Coral Sr/Ca analysis" was just one standard or known value used in the ICP analysis? Most labs use 2 or 3 (a gravimetric, a coral, and JCP international standard). The Schrag (1999) and de Villiers et al. (2002) methods bracket each sample for drift correction. which is typical for ICP-OES whereas every 5th sample is used for ICP-MS since that instrument does not drift as much. The exact analytical precision(s)±1sigma should be given with # of measurements and error bars of analytical precision on all graphs with coral Sr/Ca. It would also be good to see the raw Sr/Ca values plotted, not just anomalies. It is difficult to gauge the individual records from the anomaly plots alone.

In total, 5 different CRM were used, including the international CRM JCp-1 and JCt-1. They were measured before and after the entire measurement sequence. We will explain this in more detail in the methods section in a revised version. Furthermore, we added error bars on all coral Sr/Ca graphs. During method development for Sr/Ca analysis we started off with standard-sample-standard bracketing as in Schrag et al. (1999) but found that inserting 6 samples did not compromise our results at all. (We re-measure every 12th coral sample at the end of each measurement run, and we find no evidence of drift problems). A similar strategy is also used in isotope geochemistry. The resulting uncertainty of 0.8 permil (1SD) in our data is speaking for itself and is much better than all ICP-MS data we know of. The very general statement of reviewer 2 that ICP-OES instruments drift more than ICP-MS instruments is not valid, at least for our instrument.

In section 3.3 "Chronology" the authors suggest that they only use the minima of seasonal SST cycles as their chronological tie points, but their chronology would likely be more robust if they used at least 2 ties points (maxima and minima) for time assignment.

See our comment below reviewer comment RC2 - 4. Note: at Chagos there are two SST maxima per season, one in boreal fall and one in spring. In most years, the spring maximum is largest, but this is not always the case (see Figure 3, year 2007-2009). Adding a second tie point in boreal summer therefore adds a lot of chronological uncertainty.

In section 3.5 "Statistics", it would be helpful to know which version of PAST (with citation) and MATLAB the authors used. I am confused as to why the authors chose to use the web application T-Test Calculator (web link needs to be given) rather than at-test function in the other software listed or just use a t-table in a statistics textbook. Also, in general, the authors tend not to list the α, n, or other key statistical values for their data throughout the paper (except in some figures). All averages should be report with their standard deviations, and number of values, correlations should have p-value and n, and all errors as either 1 or 2 sigma, which are standard statistical practices.

We agree, that these information should be added and we did it in the revised version.

In section 4.4, "ENSO Interannual SST variability", the authors suggest that all of their coral records show statistically robust typical ENSO periodicities (3-8 years), but fail to address varying levels of statistical robustness. Their earliest composite record (E5,Figure 6a) for example has an ENSO periodicity that is only statistically significant at the $\alpha=0.1$ level, but the authors do not discuss this in the text. Despite detrending before analysis, there is also evidence of roughly annual periodicities in both B8 (Figure6b) and E3 (Figure 6c). Figures S8-10 and S11, supplementary analyses, are cited as confirming the power spectrum analysis results, but also bring out issues in the temporal continuity of these spectra and their directionality.

Annual periodicities are still visible, because only the long-term trend was subtracted and not the annual cycle. However, as mentioned above, we exchanged this figure with figure S11 and show the wavelet coherence analysis plots instead.

The Brönnimann et al. paper was published in 2007, not 2006 (this issue could be present in other references, and should be checked).

Reference corrected.

The GIM coral data seem to have been first published in Pfeiffer et al. 2009, not 2017.

Yes, that is correct. That is why we mentioned Pfeiffer et al. (2009) in the initially submitted manuscript in the Methods and Material section (chapter 3.1; lines 122-127) as well as in figure caption of figure 6. Note that Pfeiffer et al. (2009) only present data back until 1950, not 1880.

All of the supplemental figures are mislabeled, and should be corrected. I recommend, in fact, that the entire Supplemental file be carefully reviewed and edited, as I noticed consistent issues in the labeling of materials and numerous typographical errors.

We do not see that all supplemental figures are mislabeled. However, as the other reviewer also mentioned wrong numbering of the supplementary figures, we changed the titles of each chapter in the supplementary material which may have caused the misunderstanding. In the originally submitted version, e.g. chapter 3 of the supplementary material was named 'S3 X-ray images' that included 'Figure S2'. After revision, this chapter's title is now '3 X-ray images'.
Additionally, we went through the entire supplementary file and checked for consistency.

Ln 30: The opening sentence of the introduction reads a bit awkwardly, I would suggest rewording to something like "As the impacts of global climate change increase, paleoclimate research is more important than ever". On the same line, I would remove the first word of the second sentence ("Especially") and simply begin the sentence with "The Indian Ocean...".

(l. 30) Revised.

Ln 32: should be "basin", not "basing".

(l. 31) Changed.

Ln 34: Remove "As" and begin the sentence with "Tropical corals".

(l. 34) Done.

Ln 35: the sentence here continued from

(l. 35) Done.

Ln 34 is somewhat awkwardly worded, and should be ended with "variability" not "variabilities".

(l. 35) Done.

Ln 37-39: the sentence in this section repeats its point in the second half, I would delete the section after the first citation of Pfeiffer et al. 2006.

(l. 37) Deleted.

Ln 40: change "are focusing on" to "focus on".

(l. 39) Done.

Ln 41-42: change "lack of data in" to "lack of data from", remove "still" and "the" from the phrase "still limits the" and replace "the" with "our", and change "variabilities" to the singular.

(l. 41) Done.

Ln 46: change "In fact, it was suggested" to "It is suggested".

(l. 57) Revised paragraph.

Ln 68: change "form" to "from". Also recommend moving the phrase "from October to April" from beginning to end of sentence.

(l. 85) Done.

Ln 166:"Composite" should be "Composites".

(l. 205) Revised.

Ln 200 and 203: ranges in both of these lines contain values to three significant digits, while all others reported in paper are only to two.
(l. 235) Adjusted.

Ln 293: there is a period missing between "Indian Ocean" and "For".
(l. 341) Inserted.

Ln 308: the end of the sentence here should read "Brönnimann et al. (2006) (Table 6)".
(l. 275) Revised.

Ln 313: should read "Indian" not "India" monsoon.
Deleted entire paragraph.

Ln 337: remove the "events" before "non-La Niña", and make sure to correct the spelling of La Niña.
(l. 393) Done.

Additional Comments in Manuscript PDF (initial text of the manuscript with line numbers and in italic, reviewer comments in bold with our answer below each comment):

L 24 "All four coral records show typical ENSO periodicities, suggesting that the ENSO-SST teleconnection in the central Indian Ocean was stationary since the 17th century"
Comment 1: Abrams had a recent paper, what do they say?
For a detailed reply, see our comment below the reviewer comment RC2 – 11.

L 37: "There are only some studies including Sr/Ca measurements for SST reconstructions (e.g. Pfeiffer et al., 2006),…"
Comment 2: if there are few, why not list them to be comprehensive and not just cite the authors own papers. I count 7 studies so is that really a few? Hennekam 2018 doi: 10.1002/2017PA003181 Zinke 2014 doi: 10.1038/ncomms4607 Zinke 2004 doi: 10.1016/j.epsl.2004.09.028Zinke 2008 doi:10.1029/2008GL035634.Zinke 2016 doi: 10.5194/bg-13-5827-2016 Bryan 2016 doi: 10.5194/bg-13-5827-2016Abram 2020 https://doi.org/10.1038/s41586-020-2084-4
(l. 37-41) We added missing literature mentioned above. For a detailed reply see our comment below reviewer comment RC2-9.

L 40: "…and/or are sampled at only bimonthly (Zinke et al., 2004; Zinke et al., 2008) or annual resolution (Zinke et al., 2014; Zinke et al, 2015)"
Comment 3: Bimonthly meaning every two months or sampled twice per month?
Regardless, bimonthly is probably fine for resolving the seasonal cycle, just as well as, monthly. So what is the point you are trying to make here?
(l. 40) Bimonthly means in this case every two months. For resolving the seasonal cycle, it is of course better to have 12 values per year than 6 values.

L 45: "Strong El Niño Southern Oscillation (ENSO) events occur more frequently since the early 1980s (Baker et al., 2008; Sagar et al., 2016)…"
Comment 4: El Nino are the events, SOI is the cycle between SLP between Darwin and Tahiti linked to walker circulations and includes EL nino and la nina events.
REvise to El Nino events only.
(l. 44) Revised.

L 46: "…demonstrating an existing stable SST-ENSO teleconnection between the Pacific Ocean and Indian Ocean…"

Comment 5: How do you know this is stable? The premise of your paper is to assess if it weakens or exists in the past 200 years. Delete "stable"

(l. 52) With "stable" we meant "stationary". We see that we did not explain it very well. We defined what we mean with "stationary" in the revised version.

L 49: "This asymmetric ENSO teleconnection has been suggested to contribute to the overall 50 warming of the tropical Indian Ocean."

Comment 6: The use of "asymmetrical" was confusing from the abstract to here. At first I thought you were referring to a spatial asymmetry but you mean a temporal or different response to La Nina-El Nino events. Scientist talk a lot about the ENSO spatial pattern so this is easy misinterpretation. Why not use a better term? Yes, Roxy 2014 use the "asymmetry' term but their paper is confusing as well. Help the reader out and explain better what is meant by asymmetrical ENSO teleconnection between Indian and Pacific oceans.

(l. 67) We agree, that we had to explain better what we mean with "asymmetrical ENSO teleconnection". We did this in the revised version.

L 53: "…the core top (1950-1995) was shown to record SST variability at Chagos on grid-SST scale (Pfeiffer et al., 2009)."

Comment 7: Explain what grid-SST scales are? Do you mean a particular gridded SST data product(s)?

Pfeiffer et al. used ERSST version 2, but that data was consistent with other SST products such as HadISST.

L 55: "We identify past warm and cold events in each record and use these events to compile composites to evaluate the symmetry of positive and negative ENSO-driven SST anomaly events in the tropical Indian Ocean."

Comment 8: By Symmetry you mean the magnitude of the La nina nad El nino events are the same or not. Why not just say you are looking at magnitude differeneces?

(l. 70) As mentioned above, we explained what we mean with "ENSO asymmetry" in the revised version. The concept is widely used in conceptual papers on ENSO and ENSO teleconnections

Comment 9: Roxy 2014 Fig 5 shows Western Indian Ocean has most of this warmer El nino events, not the central Indian ocean.

We agree, that the western Indian Ocean is most affected by warming as shown in Roxy et al., 2014 using HadISST data. However, this warming trend is still visible in the Seychelles-Chagos-Thermocline-Ridge region, which also suffers from a lack of observations on historical timescales (see Pfeiffer et al., 2017; https://doi.org/10.1038/s41598-017-14352-6). Furthermore, depending on the SST dataset, warming in the Indian Ocean is largest in the Arabian Sea (Roxy et al., 2014) or in the central Indian Ocean (Roxy et al., 2020; http://www.rocksea.org/bin/research/roxy_indian_ocean_warming_climate_change_assessment_2020.pdf). Besides, in our conclusions we suggest compiling composite records of negative and positive SST anomaly events from sub-fossil corals from the western Indian Ocean to further test Roxy et al.'s hypothesis of an asymmetric ENSO teleconnection in the western Indian Ocean.

L 59: "The Chagos Archipelago is located in the tropical Indian Ocean, about 500 km south of the Maldives."

Comment 10: can you provide a latitude and longitude to be more specific?

(l. 76) Done.

L 90: "A coral-based reconstruction of past IOD events extends until 1846 and suggests a recent intensification of the IOD (Abram et al., 2008)."

Comment 11: **Should add more recent paper by Abram 2002. https://doi.org/10.1038/s41586-020-2084-4**

(l. 107) Added. For a detailed reply, see our comment below the reviewer comment RC2 – 11.

L 101: "Both anomaly records are not significantly different (t-value = 0.34; p-value = 0.37)."

Comment 12: 2011 la nina has different magnitudes.

(l. 120) We are not sure what the reviewer wants to point at with this comment.

L 102: "This suggests that the magnitudes of ENSO signals at Chagos should be recorded in all coral records analyzed in this study, as it is independent from the reef setting."

Comment 13: **You cannot say this for all time I would drop the last part of this sentence.**

(l. 121) Revised.

L 154: "…measured in 2017 in the HISPEC laboratory of the Department of Geosciences, NTU, following techniques described in Shen et al. (2012). These age determinations are consistent with our Sr/Ca chronologies."

Comment 14: **what about dating uncertainties? were U-th a single annual band? how and where were these taken, please mark x-ray images to dating samples.**

We marked where the U/Th samples were taken on the X-ray images (Figure S2). The age model was developed in the following way: For each coral sample: 1st age dated by U/Th (in 2016) → from this age band the years were counted on the x-ray images (and combined with raw Sr/Ca) → upper or lower most counted year was compared with 2nd age dated by U/Th (in a second measurement run in 2017). As every second age that was dated with the second U/Th measurement fitted to the age model developed using the x-rays and raw Sr/Ca data, dating uncertainties due to sampling for U/Th measurements are neglectable.

L 160: "…analysis were selected from all corals based on the X-ray images."

Comment 15: **please mark x-ray where these samples were located? were they along your sampling path?**

Figure revised (Fig. S2).

L 170: "Power spectra analysis was performed twice using the open source software PAST (Hammer et al., 2001)"

Comment 16: what windows, smoothing, etc. please provide more info.
Why use these software programs? did you do more than remove a linear trend? What do these programs do? Why not just filter like cobb 2013 and many others who look at coral and ENSO?

We moved these parts of the methods to the Supplementary Material document as it describes methods used for analysis that was also moved to the Supplementary Material. There, we added additional information of the software PAST. PAST (Paleontological Statistics) is an open source software with a lot of different functions. We used it for Power Spectrum analysis (REDFIT function, Welch window, Oversample: 2-8, Segments: 4-6). As mentioned in the methods section, we did not use PAST, but *breakfit* and *rampfit* for detrending. Detrending was necessary to compile the composite records. We then also used this detrended data for the power spectrum analysis. These programs are able to remove not only linear trends (which was the case with E3 and GIM as it can be seen in Figure S7 of the revised version of the supplementary material), but they find breakpoints in time series where long-term trends change and calculate linear functions for these periods which are used for subtracting these long-term trends from the original time series. For example, coral record E5 in Figure S7 shows 4 linear graphs in red that were calculated with these programs overlying the original time series.

L 175: "…and wavelet coherence plots were generated using the MATLAB software toolboxes."

Comment 17: **citation**

(l. 202) Added.

L 178: SE equation
Comment 18: **this is for a mean, not all errors.**
(l. 212) Revised.

L 212: "The modern and the sub-fossil coral SST records were compared with the annually resolved El Niño index Niño3.4 that extends back until 1607 (Wilson et al., 2010)…"
Comment 19: **Nino3.4 already has been used and defined in the literature, why not just call it Wilson Nino to make if clear which data set you are referring to.**
(l. 128) We renamed the *Niño3.4* index in the revised version. It is now referred to as 'Wilson Niño Index'.

L 223: "All coral records show variations in the frequency of ENSO events (Figs. 7-9 and Tables 4-6)."
Comment 20: **reference figures before explaining them.**
(l. 269) We revised this paragraph to shorten the interpretation on ENSO frequency and to make our focus more central.

L 610: Figure 3
Comment 21: **Y-axis should be labled SST anomalies**
(l. 674) Done.

L 615: Figure 4
Comment 22: **Cannot read this figures, lines and text to small. Fix this. Middle figure is missing a y-axis.**
what slope did you use?
Why not just band pass filter?
(l. 680) We included a larger version of this figure in the revised version. We used the slope -0.06 mmol/mol per 1°C as described in l. 261 of the initially submitted manuscript. However, we moved this paragraph up to the methods section of the revised version.
A detailed calibration for modern corals from the same site (Chagos Archipelago) was presented in Leupold et al., 2019 (https://doi.org/10.1029/2018GC007796). In this study, the regression of coral Sr/Ca with satellite data indicates a significant correlation (r-squared: 0.62, p<<0.01, n=265).
We are not sure why the reviewer is suggesting using band pass filter related to what is shown in Figure 4.

L 625: Figure 6
Comment 23: **Do all in years, not months! make log log plots. This is confusing since you do not have units on the frequency. looks like a-d are in months and not years. Put units on all graphs. time interval for ERSST.**
See our comment below the first technical comment by the reviewer regarding Figure 6.

L S109: Figure S11
Comment 24: **How do you do this? Nino 3.4 is modern SST.**
(l. 128) We agree, that we used the term Nino3.4 in a way that led to confusions. In this case, wavelet coherence analysis was performed for each coral Sr/Ca record with the Nino3.4 index by Wilson et al., 2010. This index extends beyond the instrumental period, until 1607. We changed the name of this index. It is now referred to as 'Wilson Niño Index'.

ENSO and internal sea surface temperature variability in the tropical Indian Ocean since 1675

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Abstract. The dominant modes of climate variability on interannual timescales in the tropical Indian Ocean are the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole. El Niño events have occurred more frequently during recent decades and it has been suggested that an asymmetric ENSO teleconnection (warming during El Niño events is stronger than cooling during La Niña events) caused the pronounced warming of the western Indian Ocean. In this study, we test this hypothesis using coral Sr/Ca records from the central Indian Ocean (Chagos Archipelago) to reconstruct past sea surface temperatures (SST) in time windows from the mid-Little Ice Age (1675-1716) to the present. Three sub-fossil massive *Porites* corals were dated to the 17-18th century (one sample) and 19-20th century (two samples), and were compared with a published, modern coral Sr/Ca record from the same site. All corals were sub-sampled at a monthly resolution for Sr/Ca measurements, which were measured using a simultaneous ICP-OES. Wavelet coherence analysis shows that interannual variability in the four coral records is driven by ENSO, suggesting that the ENSO-SST teleconnection in the central Indian Ocean was stationary since the 17^{th} century. To determine the symmetry of El Niño/La Niña events, we compiled composite records of positive and negative ENSO-driven SST anomaly events. We find similar magnitudes of warm and cold anomalies indicating a symmetric ENSO response in the tropical Indian Ocean. This suggests that ENSO is not the main driver of central Indian Ocean warming.

1 Introduction

As the impacts of global climate change increase, paleoclimate research is more important than ever. The Indian Ocean is of major relevance to global ocean warming as the western Indian Ocean has been warming faster than any other ocean basin during the last century and is the largest contributor to the current rise of global mean sea surface temperatures (Roxy et al., 2014).

Tropical corals can be used to reconstruct past changes of environmental parameters, such as sea surface temperatures (SST), by measuring Sr/Ca. They can help to determine changes in past climate variability. Most coral paleoclimatological studies covering periods before 1900 conducted in the tropical Indian Ocean predominantly focused on $\delta^{18}O$ measurements (e.g. Abram et al., 2015; Charles et al., 2003; Cole et al., 2000; Nakamura, et al., 2011; Pfeiffer et al., 2004). Several studies included Sr/Ca measurements for SST reconstructions in the central, tropical Indian Ocean (Pfeiffer et al., 2006, 2009; Storz et al., 2013; Zinke et al., 2016), while others focused on the western or the eastern Indian Ocean (Abram et al., 2003; Abram et al., 2020; Hennekam et al., 2018; Watanabe et al., 2019) and/or on corals sampled at only bimonthly (Zinke et al., 2004; Zinke et al., 2008) or annual resolution (Zinke et al., 2014; Zinke et al, 2015). The lack of monthly resolved coral Sr/Ca data from the central, tropical Indian Ocean limits our understanding of its response to transregional climate phenomena, as these are phase-locked to the seasonal cycle and vary with season.

Past El Niño Southern Oscillation (ENSO) variability on seasonal and interannual timescales has been reconstructed using corals from different settings in the Pacific Ocean (e.g. Cobb et al., 2003, 2013; Freund et al., 2019; Grothe et al., 2019; Lawman et al., 2020; Li et al., 2011), where ENSO is centered. Strong events associated with ENSO occur more frequently since the early 1980s relative to past centuries (Baker et al., 2008; Freund et al., 2019; Sagar et al., 2016). An intensification of future extreme El Niño/La Niña events under global warming is supported by paleoclimate studies using corals from the central tropical Pacific Ocean (Grothe et al., 2019). Although ENSO is centered in the tropical Pacific Ocean, ocean-atmosphere parameters of the Indian Ocean are influenced by ENSO, which was shown in coral-based SST reconstructions of ENSO variability (e.g. Abram et al., 2008; Marshall and McCulloch, 2001; Storz and Gischler, 2011; Zinke et al., 2004). Strong El Niño/La Niña events influence the tropical Indian Ocean demonstrating a stationary SST-ENSO teleconnection between the Pacific and Indian Ocean (Charles et al., 1997; Cole et al., 2000; Pfeiffer and Dullo, 2006; Wieners et al., 2017). El Niño events cause a basin-wide warming of the Indian Ocean in boreal winter (December-February), while La Niña events cause cooling (Roxy et al., 2014). However, it has been suggested that El Niño events have a stronger influence on the Indian Ocean SSTs than La Niña events, i.e. the warming during El Niño events is larger than the cooling during La Niña events (Roxy et al., 2014). In their study, Roxy et al. (2014) suggest that this asymmetric ENSO teleconnection is one reason for the overall warming of the western Indian Ocean. The positive skewness of SST in the ENSO region of the tropical Pacific is due to ENSO asymmetry, i.e. it reflects the fact that El Niño events are often stronger than La Niña events (Burgers and Stevenson, 1999; An and Jin, 2004). At teleconnected sites, such as the tropical Indian Ocean, the response to El Niño and La Niña may be asymmetric as well, as suggested by Roxy et al. (2014). However, teleconnected sites may also show a symmetric response to El Niño and La Niña events (e.g. Brönniman et al., 2007).

As the impact of ENSO on SSTs in the central Indian Ocean is recorded in coral Sr/Ca records (e.g. Pfeiffer et al., 2006), we test the hypothesis of an asymmetric ENSO teleconnection as a driver of Indian Ocean warming. We use coral Sr/Ca records from three sub-fossil massive *Porites* corals covering periods of the Little Ice Age (1675-1716, 1836-1867), and the mid-19th to early 20th century (1870-1909) as well as a 20th century coral core (1880-1995) from the central Indian Ocean (Chagos Archipelago) to reconstruct past SST variability. In this study, the concept of 'asymmetric' and 'symmetric' ENSO teleconnection refers to the magnitudes of warming/cooling during El Niño/La Niña events., i.e. we examine whether Indian Ocean warming during El Niño events is stronger than cooling during La Niña events. First, we determine whether ENSO variability is recorded in all coral Sr/Ca records from Chagos, then we identify past warm and cold events in each coral record and compile composites of warm and cold events. We then compare the magnitudes of positive and negative ENSO-driven SST anomalies in the Chagos coral Sr/Ca records and discuss whether or not they provide evidence for an asymmetric ENSO teleconnection in the tropical Indian Ocean.

2 Regional setting

2.1 Location

The Chagos Archipelago is located in the tropical Indian Ocean (70-74° E; 4-8° S), about 500 km south of the Maldives. It consists of several atolls with islands, submerged and drowned atolls, and other submerged banks with the Great Chagos Bank being the world's largest atoll (Fig. 1). The Great Chagos Bank covers an area of 18.000 km^2 with eight islands totaling 445 ha of land. Its lagoon has a maximum depth of 84 m and a mean depth of 50 m. Due to its large size and submerged islands, water exchange with the open ocean is substantial. The Salomon atoll is located about 135 km towards the northeast of Eagle Island. Its atoll area is about 38 km^2 and has an enclosed lagoon and an island area > 300 ha. The greatest depth of its lagoon is 33 m, with mean depth of 25 m.

2.2 Climate

Chagos is situated in a region characterized by monsoon climate (Sheppard et al., 2012). The austral summer is the wet season, with the Northeast monsoon lasting from October to February (Pfeiffer et al., 2004). Light to moderate north-west trades blow. During the rest of the year, strong winds from the southeast dominate from April to October (Sheppard et al., 1999).

Chagos lies at the eastern rim of the so-called Seychelles-Chagos thermocline ridge (SCTR). Along that region, a shallow thermocline causes open-ocean upwelling of cold waters. Upwelling along this region was first identified by McCreary et al. (1993) and is forced by both negative and positive wind stress curl (Hermes and Reason, 2009; McCreary et al., 1993). Compared to other upwelling regions of the Indian Ocean, the sea surface temperatures of the SCTR are relatively high. They vary between 28.5°C and 30°C in austral summer. The SCTR is believed to play a major role in the climate variability of this region on different timescales (e.g. Hermes and Reason, 2008; Vialard et al., 2009) with very strong air-sea interaction due to open ocean upwelling combined with relatively warm SST (Sheppard et al., 2012).

On interannual timescales, the dominant mode of climate variability in the SCTR is the El Niño Southern Oscillation (ENSO). During El Niño events, the West Pacific warm pool is displaced towards the East resulting in cooler than normal SST in the Western Pacific and a basin-wide warming of the Indian Ocean (Izumo et al., 2014; Sheppard et al., 2013). Figure 2 compares the positive SST anomalies during El Niño with the negative SST anomalies during La Niña events in the Indian and Pacific Ocean between 1982 and 2016, as inferred from 'Reynolds' OI v2 SST data (Reynolds et al., 2002; averaged over December-February). Even if not as strong as in the Pacific Ocean, an ENSO response in the tropical Indian Ocean can be observed (Fig. 2). Coupled ocean-atmosphere instabilities centered in the tropical Indian Ocean result in Indian Ocean Dipole (IOD) events (Saji et al., 1999; Sheppard et al., 2013; Webster et al., 1999). A negative (positive) IOD event is defined by warmer (cooler) than normal SST in the eastern part of the Indian Ocean and cooler (warmer) than normal SST in the western Indian Ocean. Several studies showed that the IOD is an inherent mode of variability of the Indian Ocean (e.g. Ashok et al., 2003; Krishnaswamy et al., 2015; Saji et al., 1999; Webster et al., 1999). However, IOD events tend to co-occur with El Niño/La Niña events (e.g. Luo et al, 2010; Saji and Yamagata, 2003). The instrumental record of past IOD events does not go back further than 1960 (Saji and Yamagata, 2003). Coral-based reconstructions of past IOD events over the past millennium suggest a recent intensification of the IOD (Abram et al., 2008; Abram et al., 2020). The corals show few strong IOD events (i.e. 2019, 1997/98, 1961, 1877/78 and 1675), of which only three events (2019, 1961, 1675) occur independently of ENSO. However, neither in 1675 nor in 1961 a positive anomaly can be found in our coral SST records. We therefore decided to treat positive SST anomaly events found in our records as El Niño events even if they could be a result of IOD events independent from or overlapping with El Niño/La Niña events.

2.3 Instrumental data

High-resolution SST data of the AVHRR satellite product (Casey et al., 2010) reveal different mean SST and seasonality at Chagos depending on the reef setting (Leupold et al., 2019; Fig. 3; 28.1±0.9°C for the open ocean reef and 28.5±0.6°C for the lagoon setting averaged over the period 1997-2012). At the open ocean reefs, where upwelling occurs, seasonal minima in SST are colder than in the lagoon, whereas maximum temperatures are not significantly different (t-value = 0.27; p-value = 0.79). Averaged over the entire area of the Chagos (70-74° E; 4-8° S), SST is similar to SST measured in the lagoon. Long-term monthly SST anomalies (i.e. mean seasonal cycle removed) reveal that extreme SST events, such as El Niño in 1997/98 or La Niña in 2010/11, have the same magnitude in both lagoon and open ocean settings (Fig. 3b). Both anomaly records are not significantly different (t-value = 0.34; p-value = 0.37). This suggests that the magnitudes of ENSO signals at Chagos should be recorded in all coral records analyzed in this study.

2.4 ENSO indices

The instrumental record of past El Niño/La Niña events is restricted to the late 19th and early 20th century. Reconstructions of past ENSO events differ depending on the statistics and/or proxies used (see e.g. Wilson et al., 2010 and Brönnimann et al., 2007 for a discussion). We therefore use different ENSO indices for comparison with our coral data presented briefly in the following. The annual El Niño Index *Niño3.4* (Wilson et al., 2010), which was reconstructed using data from the central Pacific (corals), the TexMex region of the USA (tree rings) and other regions in the Tropics (corals and an ice core), was used as a time series of past El Niño/La Niña events that extends beyond the instrumental period, until 1607. In this study, the El Niño

Index *Niño3.4* by Wilson et al. (2010) is further referred to as 'Wilson Niño Index'. We use the Wilson Niño Index for comparison with our coral SST records performing Wavelet Coherence Analysis in the time domain (see section 4.4). Data on the occurrence and magnitude of historical El Niño/La Niña events have been taken from Brönnimann et al. (2007), who combined several reconstructed ENSO indices, climate field reconstructions and early instrumental data, and evaluated them for consistency. Their reconstruction period extends back to 1500 (La Niña events) and 1511 (El Niño events), respectively. We also include the classical ENSO reconstruction of Quinn (1993), which extends back until 1500. As this reconstruction is based on historical observations of various aspects of ENSO, it should be relatively independent from statistical biases. Both records (Quinn, 1993; Brönnimann et al., 2007) cover all our coral time windows, including our 17th century coral record. By including the original list of Quinn (1993), alongside with the updated list of Brönnimann et al. (2007), we aim to evaluate the sensitivity of our analysis to different ENSO reconstructions. We use both indices by Quinn (1993) and Brönnimann et al. (2007) for identifying past warm and cold events in each coral record and we use these events to compile composites (see section 4.5).

3 Methods and materials

3.1 Coral collection and preparation

For this study, three sub-fossil coral samples were collected in February 2010, from boulder beaches and derelict buildings of former settlements at Chagos (Fig. S1). The sub-fossil corals record 41 years of a period from the mid-Little Ice Age (1675-1716), which coincides with the Maunder Minimum, a period of reduced sunspots observations (Eddy, 1976), 31 years of the late Little Ice Age (1836-1867) and 39 years of the mid-19th to early 20th century (1870-1909). Samples E3 (1870-1909) and E5 (1675-1716) were taken from Eagle Island (S 6°11.39'; E 71°19.58'), an island on the western rim of the Great Chagos Bank (Fig. 1). Sample B8 (1836-1867) was taken from the lagoon-facing site of Boddam Island (S 5°21.56'; E 72°12.34') in the southwestern part of the Salomon atoll. The samples were cross-sectioned into 0.7-1.0 cm thick slabs and X-rayed with a Faxitron X-ray model 43885 operated at 50 keV for 1-2 minutes and used together with a Konica-Minolta Regius ∑ RC 300 reader. From the slabs of each sub-fossil coral, powder samples were drilled at 1 mm increments using a micro-milling machine (type PROXXON FF 500 CNC). This depth resolution can be translated to monthly temporal resolution with average growth rates being 12 mm/yr. The subsampling paths were always set along the optimal growth axis that was determined based on x-ray images (Fig. S2).

Core GIM, a modern coral core, was included in the coral composite of the SCTR (Pfeiffer et al., 2017). This composite comprises cores from the Seychelles and Chagos. Additionally, the core top (1950-1995) of the GIM core has been calibrated with SST (Pfeiffer et al., 2009). Core GIM, was drilled underwater in 1995 in the lagoon of Peros Banhos, located in the northwest of Chagos, from a living coral colony. The monthly coral Sr/Ca record of GIM extends from 1880-1995. Analytical procedures have been described in Pfeiffer et al. (2009). In this study, we use this core to estimate the magnitude of modern El Niño/La Niña events.

3.2 Coral Sr/Ca analysis

Sr/Ca ratio measurements were performed at Kiel University using a Spectro Ciros CCD SOP inductively coupled plasma optical emission spectrometer (ICP-OES) following a combination of techniques described by Schrag (1999) and de Villiers et al. (2002). Elemental emission signals were simultaneously collected and subsequently drift corrected by sample-standard bracketing every six samples. Between 0.13 and 0.65 mg of coral powder was dissolved in 1.00 mL 0.2 M HNO_3. Prior to analysis, the solution was diluted with 0.2 M HNO3 to a final concentration of approximately 8ppm Calcium. Strontium and Calcium intensity lines used are 421 nm and 317 nm, respectively. The intensities of Strontium and Calcium were converted into Sr/Ca ratios in mmol/mol. Before and after each measurement sequence (n = 448 measurements), a stack of 8 different reference materials, including the international reference materials, JCp-1 and JCt-1 (Hathorne et al., 2013), were measured and used for calibration. For drift-correction, an in-house coral reference standard (Mayotte coral) was used. Average analytical precision of Sr/Ca determinations is 0.08% relative standard deviation (RSD) or 0.008 mmol/mol (n = 1973), translating into a temperature of around 0.1°C. The reproducibility of Sr/Ca ratios from multiple measurements both on the same day and on consecutive days is 0.08% RSD (n = 238; 1SD), translating into a temperature uncertainty of around 0.1°C.

3.3 Chronology

Each sub-fossil coral sample was dated by U-Th in 2016. U-Th isotopic measurements were performed with an MC-ICPMS (Thermo Electron Neptune) in the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC) of the Department of Geosciences, National Taiwan University (NTU), following techniques described in Shen et al. (2012). U-Th isotopic compositions and concentrations are listed in Table 1.

Sample E5 covers the period from 1675 to 1716, herein further referred to as E5 (1675-1716). Sample B8 covers the period from 1836 to 1867, E3 from 1870 to 1909, both referred to as B8 (1836-1867) and E3 (1870-1909), respectively. The uncertainties of the age models are approximately ±1.9 years (E5), ±2.2 years (B8) and ±2.4 years (E3). All age models were verified by a second, independently measured U-Th age of each sample, measured in 2017 in the HISPEC laboratory of the Department of Geosciences, NTU, following techniques described in Shen et al. (2012). These age determinations are consistent with our Sr/Ca chronologies.

The chronology of the samples was developed based on seasonal cycles of coral Sr/Ca and by analyzing the density bands visible on x-ray images (Fig. S2). We assigned the highest Sr/Ca value to the SST minimum of each year and interpolated linearly between these anchor points to obtain a time series with equidistant time steps.

3.4 Diagenesis screening

A combination of X-ray diffraction (XRD), optical and scanning electron microscopy (SEM) was used to investigate potential diagenetic alteration in the sub-fossil coral samples from Chagos that may affect the Sr/Ca values (Figs. S3, S4, and S5).

Representative samples for thin-section, scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis were selected from all corals based on the X-ray images. The 2-D-XRD system Bruker D8 ADVANCE GADDS at the Rheinisch-Westfaelische Technische Hochschule (RWTH) Aachen was used for non-destructive XRD point-measurements directly on thin-section blocks with a calcite detection limit of ~ 0.2 % (Smodej et al., 2015). For each coral sample diagenetic modifications were analyzed using one thin-section, one sample for SEM, one 2D-XRD measurement and one powder-XRD measurement.

3.5 Statistics

All coral Sr/Ca records were centered, i.e. normalized with respect to their mean values (Pfeiffer et al., 2009) and translated into SST using a temperature dependence of -0.06 mmol/mol per 1°C for *Porites* corals at Chagos (Leupold et al., 2019; Pfeiffer et al., 2009).

Wavelet coherence plots between the coral Sr/Ca records and the Wilson Niño Index were generated using the *MATLAB* (version R2019b) software toolboxes by Groth and Ghil (2015) to assess whether the interannual variability recorded in the corals is related to ENSO.

Composites of El Niño and La Niña events were generated by calculating the mean of positive and negative anomaly events taken from centered monthly coral SST anomaly records. By centering the coral records to their mean and focusing on interannual variability, we eliminate the largest uncertainty of single-core Sr/Ca records, as shown by Sayani et al. (2019).

T-tests were conducted using the free web application *T-Test Calculator* (GraphPad QuickCalcs, 2019; https://www.graphpad.com/quickcalcs/ttest1/, last access: 09 April, 2019). T-tests were used to determine if the mean values of two data sets, e.g. mean annual cycles in chapter 4.3 or mean anomalies of coral composites in chapter 4.5, are significantly different from each other.

As the significance of the monthly mean anomalies calculated for the composite records depends on the numbers of events, standard errors (SE) for monthly mean anomaly values were used and calculated as follows:

$$SE = \frac{\text{standard deviation } (\sigma)}{\sqrt{\text{Number of events } (n)}}, \quad (1)$$

4 Results and Interpretation

4.1 Diagenesis

Only trace amounts of diagenetic phases were detected in the sub-fossil coral samples, which show a good to excellent preservation according to the criteria defined in Cobb et al. (2013). Isolated scalenohedral calcite cement crystals were observed in the thin-section of E5 (1675-1716) (Fig. S3 a-d). However, XRD results and SEM analysis confirm that the calcite abundance is below the detection limit of XRD (0.2%) in this sample (Fig. S3 e-f). B8 (1836-1867) shows trace amounts of patchily distributed, thin aragonite cements (Fig. S4). E3 (1870-1909) is devoid of diagenetic phases (Fig. S5), but in some areas of the thin-section dissolution of centers of calcification can be seen (Fig. S5 c-d). Slight dissolution and microborings are also visible under SEM (Fig. S5 f). However, microborings are always open and therefore will not influence the geochemistry. In summary, diagenesis screening revealed that the coral samples are suitable for conducting geochemical analysis and diagenetic modifications to the Sr/Ca records should be neglectable.

4.2 Sr/Ca measurements

Table 2 gives an overview of the Sr/Ca ratios of each sub-fossil coral core and statistical key figures of the records. The values are shown in Figure 4.

4.2.1 17-18th century

A total of 472 subsamples from E5 (1675-1716) was measured for Sr/Ca. The average Sr/Ca value is 8.96 ± 0.07 mmol/mol (n = 472). The maximum range of all Sr/Ca values over the 41-year sample span is 0.41 mmol/mol, between a minimum of 8.73 mmol/mol and a maximum of 9.14 mmol/mol.

4.2.2 19-20th century

From B8 (1836-1867), Sr/Ca of 375 subsamples was measured. The average value is 9.02 ± 0.07 mmol/mol (n = 375) over a range of 0.51 mmol/mol. The maximum Sr/Ca value for the 31-year sample span is 9.36 mmol/mol, the minimum Sr/Ca value is 8.85 mmol/mol.

For E3 (1870-1909), Sr/Ca measurements were conducted on 415 subsamples. The average Sr/Ca value is 8.95 ± 0.06 mmol/mol (n = 415) for the 39-year sample span, over a range of 0.38 mmol/mol from a minimum value of 8.79 mmol/mol to a maximum of 9.17 mmol/mol.

4.3 Decadal variability and seasonal cycle

All coral SST records show variability on decadal scale (Fig. 4). Such decadal variability in the Indian Ocean was already described in previous studies (Charles et al., 1997; Cole et al., 2000; Pfeiffer et al., 2006, 2009; Zinke et al., 2008), and the typical periodicity is 9-13 years. Within a decadal cool/warm phase, negative/positive SST anomalies may occur. In particular, high-amplitude, short-term cool events are possible as Chagos lies in a region where open ocean upwelling occurs (see Leupold et al., 2019). To ensure that decadal variability does not influence the composite records (by inflating interannual warm or cool anomalies), decadal variability is removed by detrending the coral records.

The mean annual cycles of all sub-fossil coral SST records are not significantly different as indicated by p-values around 1 in the t-tests (Table 3, Fig. 4). The seasonal amplitudes in coral SST (°C) are slightly higher in E5 (1675-1716) (1.99°C) compared to B8 (1836-1867) (1.81°C) and E3 (1870-1909) (1.71°C). A shift of mean maximum temperatures from February (E5 and B8) to April (E3) can be observed (Fig. 4). Seasonal amplitudes explain 26-32% of the coral-SST variance (see supplementary material and Fig. S6).

4.4 ENSO signals in coral SST records

The modern and the sub-fossil coral SST records were compared with the annually resolved Wilson Niño Index that extends back until 1607 (Wilson et al., 2010). All coral records show positive and negative SST anomalies, which occur in years where El Niño/La Niña events have been reported (Fig. 5). To analyze a possible correlation between the coral SST records and ENSO, Wavelet Coherence (WTC) was conducted on all coral records and the Wilson Niño Index (Wilson et al., 2010). Wavelet Coherence (WTC) plots were generated to find regions in time-frequency space where the Wilson Niño Index and the Chagos coral SST records co-vary, even if they do not have high power in those regions (Fig. 6).

All WTC plots of the Wilson Niño Index and coral SST records reveal time-localized areas of strong coherence occurring in periods that correspond to the characteristic ENSO cycles of two to eight years. The WTC plots for the Wilson Niño Index and the 19-20th century coral records show several regions where both time series co-vary. In contrast, the WTC plot of the Wilson Niño Index and the 17-18th century coral SST record shows only one region of co-variation at the beginning of the 18th century. The plots show that there is an approximate lag of 9 months to one year between the 17-18th century coral SST record and the Wilson Niño Index (Fig. 6a), and an approximate 1-3 year lag between B8 (1836-1867) and E3 (1870-1909) and the Wilson Niño Index, respectively, (Figs. 6b & c). However, the lags between the coral SST and the index time series are in the range of the age model uncertainties of the sub-fossil corals, and do not represent real time lags. For a further comparison of the coral SST records' and the Wilson Niño Index' frequencies, singular spectrum analysis and power spectra of non-detrended and detrended time series were computed (see supplementary material).

All coral records show anomaly events that can be explained with El Niño/La Niña events listed in Quinn (1993) or Brönnimann et al. (2007) (Tables 4-6). Our results show that, compared to the 17-18th century, more El Niño/La Niña events per period are recorded in coral records of the central Indian Ocean in recent periods. According to the AVHRR satellite data and coral records, an El Niño event occurs on average every 4 years between 1981 and 2017 (AVHRR) or every 5 years between 1965 and 1995 (coral record), respectively (Tables 4-6). This is supported by the events listed in Quinn (1993), and reflects a change in ENSO frequency in the tropical Pacific. Overall, predominantly strong El Niño events are recorded by the coral records from Chagos, as indicated in the list of events presented in (Brönnimann et al. (2007) (Table 6). The number of events listed in Brönnimann et al. (2007) is comparable to the number of events recorded in the corals, whereas the number of events listed in Quinn (1993) is higher compared to the events recorded in the corals. The same holds for the negative SST anomaly events (La Niña and non-La Niña events): the number of La Niña events listed in Brönnimann et al. (2007) is similar to the number of negative anomaly events recorded in the coral records. Furthermore, based on the AVHRR satellite data and the coral records, negative anomaly events occurred every 2.6 years (AVHRR) and every 6 years in the coral record or every 5 years in Brönnimann et al. (2007) between 1965 and 1995, respectively. During the 17-18th century, negative SST anomalies occurred every 6.8 years (coral record) or 10.3 years (Brönnimann et al., 2007) (Tables 4-6).

4.5 ENSO composites

Composites of monthly coral SST anomalies were produced for El Niño/La Niña events to assess their magnitudes. Each composite was produced using coral records of several individual El Niño/La Niña events. An overview of the events used for generating each composite can be found in Table 4 and Table 5. An overview of all events found in the coral Sr/Ca records and of El Niño/La Niña events of the corresponding time periods listed in Quinn (1993) and Brönnimann et al. (2007) is given in Table 6. Positive SST anomalies in the coral records were interpreted as El Niño events when the year of occurrence was listed as one El Niño event in Quinn (1993) and Brönnimann et al. (2007) within the error of each coral age model and when the anomaly exceeds 1.5 standard deviations of the mean of each coral record (Fig. S7). In addition to the strong La Niña events listed in Brönnimann et al. (2007), we added negative SST anomalies occurring in years after the El Niños to the composite.

The composite record for El Niño events comprises 35 events, and 31 events are included in the La Niña composite (Table 4). To investigate changes in the magnitude of ENSO anomalies over time, composites for the time periods 17-18th century and 19-20th century, respectively, were generated. For the 17-18th century, six events (five events) were used for the El Niño (La Niña) composite. The composite for the 19-20th century includes events from the sub-fossil corals and the GIM record. For the 19-20th century, 29 events (26 events) were used for the El Niño (La Niña) composite. The 19-20th century composites, in turn, were split into three sub-periods: 1830-1929 (18 El Niño events, 16 La Niña events), 1930-1964 (five El Niño events, five La Niña events; Table 5) and 1965-1995 (six El Niño events, five La Niña events). These sub-periods were chosen because ENSO activity was reduced between 1930 and 1965 compared to before 1930 and after 1965 (e.g. Cole et al., 1993).

Observations indicate that some upwelling events in the central Indian Ocean are not forced by large-scale ENSO or IOD variability but associated with cyclonic wind stress curls in the southern tropical Indian Ocean (Dilmahamod et al., 2016; Hermes and Reason, 2009). Such an upwelling event occurred in August 2002 and was found in both the coral and satellite SST records at Chagos (see Leupold et al., 2019).

To investigate the potential effect of such negative anomaly events on the La Niña composites, the 19-20th century composites were split up into composites of La Niña events and other negative anomaly events, which are not related to La Niña. La Niña and negative anomalies other than La Niña events were selected based on the months they occurred in, i.e. November-May (La Niña), June-September (Non-La Niña). As such events are also observed recently, we compared modern (1981-2018) satellite SST composites for El Niño events (nine events), La Niña events (10 events) and negative anomalies other than La Niña events (four events) with our coral SST composites. We used the AVHRR satellite SST (Casey et al., 2010) averaged over entire Chagos (4-8° S; 70-74° W).

4.5.1 Positive anomalies in coral and satellite SST composites

The coral SST composites of positive SST anomalies reveal that corals of the central Indian Ocean record higher anomalies during El Niño events compared to the satellite composites (Fig. 7), which may reflect the greater sensitivity of the corals to reef-scale temperatures (Leupold et al., 2019) or the different time periods covered by these records (only two El Niño events in the AVHRR record overlap with the coral data). The coral composite of the 17-18th century shows higher anomalies than the coral composites of the 19-20th century (Fig. 7). All positive SST anomalies identified as El Niño events in the coral records show on average a maximum value of 1.5 ± 0.1°C (n = 35; Fig. 7). The average maximum temperature anomaly value of El Niño events during the 17-18th century were 2.2 ± 0.2°C (n = 6), higher than and significantly different (p << 0.01) from the average maximum El Niño temperature anomaly during the 19-20th century (1.3 ± 0.1°C; n = 29). The average maximum temperature of El Niño events picked from the AVHRR satellite SST (covering the period from 1981 to 2018) of 0.8 ± 0.1°C (n = 9) is also lower than and significantly different (p << 0.01) from average maximum El Niño temperature anomaly in the 19-20th century. This suggests a greater impact of El Niño events on Indian Ocean SST during the 17-18th century compared to the 19-20th century and during the last decades.

4.5.2 Negative anomalies in coral and satellite SST composites

No statistically significant differences were found between negative anomalies in coral SST in the central Indian Ocean during the 17-18th century and the 19-20th century and between La Niña and non-La Niña events (Fig. 8).
All negative SST anomalies identified as La Niña and non-La Niña events in the coral records show a minimum temperature anomaly of -1.6 ± 0.1°C (n = 31) on average (Fig. 8). On average, the minimum temperature anomaly is -1.6 ± 0.1°C (n = 22) for all La Niña events and -1.5 ± 0.4°C (n = 9) for non-La Niña events during the 19-20th century of the coral SST records (p = 0.75). La Niña events in the coral records are slightly more negative than non-La Niña events, but not statistically different from non-La Niña events (p = 0.60). The same is observed in the AVHRR satellite SST anomaly composites, where average La Niña minimum temperature anomalies are -0.8 ± 0.1°C (n = 10) and non-La Niña anomalies are -0.6 ± 0.1°C (n = 4; p = 0.17).
The average minimum temperature anomalies of La Niña and non-La Niña events during the 17-18th century were slightly less extreme (-1.5 ± 0.3°C; n = 5), but not significantly different (p = 0.73) from the average minimum temperature anomalies of the 19-20th century (-1.6 ± 0.2°C; n = 26).

4.5.3 Interannual SST anomalies during the 19th and 20th century

Dividing the 19-20th century into three sub-periods (1830-1929; 1930-1964; 1965-1995) and compiling SST anomaly composites allows us to assess changes in the magnitude of ENSO-driven warm and cold anomalies over time (Fig. 9). The El Niño composites do not show any systematic changes during the 19-20th century in the Indian Ocean. For the period between 1830 and 1929, the average maximum temperature anomaly is 1.4 ± 0.1°C (n = 18), while between 1930 and 1964 the average maximum temperature anomaly of 1.2 ± 0.1°C (n = 5) is slightly less extreme than the previous period, but not significantly different (p = 0.5). For the last period of the 20th century, 1965 to 1995, the average maximum temperature anomaly is again to 1.4 ± 0.1°C (n = 6; Fig. 9).

The magnitude of cooling during La Niña and non-La Niña events tend to reduce from 1830-1929 to 1965-1995 (Fig. 9). For the period between 1830 and 1929, the average minimum temperature anomaly is -1.9 ± 0.2°C (n = 16). Between 1930 and 1964 the average minimum temperature anomaly increases by 0.58°C to -1.3 ± 0.1°C (n = 5), and for 1965 to 1995, the average minimum temperature anomaly is -1.1 ± 0.1°C (n = 5). However, for both El Niño and La Niña events, the differences between the means of the first period (1830-1929) and the last period (1965-1995) are not statistically significant (p = 0.93; p = 0.07, respectively).

5 Discussion

It has been shown that ENSO influenced SST variability of the Indian Ocean during the 19th and 20th century (Charles et al., 1997; Cole et al., 2000) and that there was a stationary ENSO-SST teleconnection, in the sense that El Niño warms the Indian Ocean and La Niña cools it (Pfeiffer and Dullo, 2006). Our results show that all coral records, covering periods of the 17-18th and 19-20th century, show interannual variability that is coherent with the Wilson Niño Index. We therefore can say that the ENSO-SST teleconnection in the central Indian Ocean was stationary since 1675.

In this study, we aim to take the analysis of the ENSO-SST teleconnection one step further: we have compiled the data in composites to estimate and compare the magnitude of ENSO-induced warming and cooling in the central Indian Ocean. This allows us to assess the symmetry/asymmetry of the ENSO teleconnection. Overall, the magnitudes of El Niño and La Niña events recorded in the Chagos coral records during the past century are comparable (Fig. 9). This suggests the ENSO teleconnection in the tropical Indian Ocean was close to symmetric. Only in times of cooler mean climates (during the 17-18th century), the corals seem to indicate higher amplitude ENSO-induced warm anomalies in the tropical Indian Ocean, although these differences are not statistically significant. Hence, our results do not support the notion that an asymmetric ENSO teleconnection with strong warming during El Niño years drives the recent warming of the tropical Indian Ocean as suggested by Roxy et al. (2014). The modern coral records from the central Indian Ocean all show a steady warming during the 20th century, and this warming continuous in the time interval of reduced ENSO activity between 1930 and 1965 (e.g. Charles et al., 1997; Pfeiffer and Dullo, 2006; Abram et al., 2016). This suggests that neither the magnitude, nor the frequency of past El Niño events explains the centennial-scale warming of the Indian Ocean.

El Niño/La Niña events recorded in our coral records and listed in Table 4 and 5 can be found as predominantly “very strong” or “strong” events listed in Quinn (1993) and Brönnimann et al. (2007) (Table 6). As it can be seen in Table 6, all positive anomaly events recorded in our coral records can be explained with one event listed in either Quinn (1993) or Brönnimann et al. (2007). Not every event listed in Quinn (1993) and Brönnimann et al. (2007) is recorded in the coral records from the central Indian Ocean. Especially the number of events in Quinn (1993) is higher compared to the events recorded in the coral records. However, the number of events listed in Brönnimann et al. (2007) is similar to the number of events recorded in the coral records (Table 6), again suggesting that predominantly strong events in the Pacific Ocean (as Brönnimann et al. (2007) only listed strong events) are recorded in the corals from the central Indian Ocean. This in turn implies, that our results are not dependent on the ENSO index used as a basis to identify events, as most reconstructions consistently record strong events.

Our results showing that El Niño events resulted in stronger SST anomalies in the central Indian Ocean corals in the 17-18th century, i.e. during a cooler mean climate, are consistent with Pfeiffer et al., (2017), who found larger amplitudes of ENSO-induced warm anomalies in the tropical Indian Ocean in the late 19th century, when mean SSTs in the tropical Indian Ocean were cooler. It is also consistent with Zinke et al. (2004) who found highest $\delta^{18}O$ amplitude variations in the interannual ENSO band between 1645–1715 in a coral from Ifaty, Madagascar. Comparing both periods, the La Niña and non-La Niña cold events show no significant changes suggesting a stable negative SST anomaly pattern in the Indian Ocean. We are not sure why this is the case. However, the tropical Indian Ocean is the warmest tropical Ocean, and recent instrumental data suggests that, as the Indian Ocean continues to warm, the temperature variability reduces particularly in the warm season, while SSTs in the cold season show strongest warming (e.g. Leupold et al., 2019; Roxy et al., 2014) and largest spatial variability (Leupold et al, 2019).

The coral records from Chagos also record upwelling events in boreal summer, which are independent of ENSO, poorly represented in satellite data of SST (see Leupold et al., 2019), and which may result in the failure of the Indian monsoon. Such an upwelling event occurred for example in 2002 and lead to a drought over the Indian subcontinent (Jayakumar and Gnanaseelan, 2012; Krishnan et al., 2006). At present, little is known about the frequency or magnitudes of these events in past decades or centuries. Coral proxy data from Chagos thus allow us to better understand these non-La Niña upwelling events.

In contrast to the stationary teleconnection between ENSO and SST in the central Indian Ocean, the ENSO-precipitation teleconnection was shown to be non-stationary (Timm et al., 2005). The impact of ENSO on rainfall in the central Indian Ocean depends on mean SSTs, and these surpassed a critical threshold for atmospheric convection in the mid-1970s, strengthening the El Niño signal in rainfall. However, our study does not indicate an increase in the magnitude of El Niño-related SST anomalies following this shift compared to earlier time periods of strong ENSO activity.

In summary, this study confirms that the ENSO-SST teleconnection between the Pacific and Indian Ocean is stationary over the 19th/20th century and back to 1675. We have shown that it is possible to reconstruct interannual SST variations in the tropical Indian Ocean. This is important because so far there exist no reliable high-resolution SST reconstructions in the Indian Ocean covering the periods we studied. SST reconstruction studies of the Pacific Ocean also show ENSO and decadal-scale variability covering the periods from 1998 back to 1886 (Cobb et al., 2001) and 928-961, 1149-1220, 1317-1464 and 1635-1703 (Cobb et al., 2003). Cobb et al. (2003) spliced three overlapping coral records of the 14-15th century and five coral records of the 17-18th century together. We have shown that this approach would be applicable in the tropical Indian Ocean using sub-fossil corals from boulder beaches and historical buildings, and if a more complete record of millennial-scale coral reconstructions from the tropical Pacific and the Indian Ocean becomes available, it will be possible to assess the ENSO teleconnection based on an analysis of the coral records from both oceans. This is important because recent studies have shown that the tropical Indian Ocean plays a pivotal role in 20th century global temperature rise (Funk et al., 2008; Roxy et al., 2014; Pfeiffer et al., 2017).

6 Conclusions

We have shown that the ENSO-SST relationship in the central Indian Ocean was stationary since the 17th century. All four coral records showed interannual variability coherent with ENSO variability, but variations in the intensity of El Niño and La Niña-induced SST anomalies in the central Indian Ocean. El Niño events cause average positive anomalies of 2.2 ± 0.2°C (n = 6) during the 17-18th century and 1.3 ± 0.1°C (n = 29) during the 19-20th century, while La Niña events cause average negative anomalies of -1.5 ± 0.3°C (n = 5) during the 17-18th century and -1.6 ± 0.2°C (n = 26) during the 19-20th century in the central Indian Ocean. However, not all cooling events are related to La Niña events, but also to processes internal to the Indian Ocean causing negative anomalies of -1.5 ± 0.4°C (n = 7) during the 19-20th century. The magnitudes of El Niño and La Niña events during the last century are comparable, indicating a symmetric ENSO teleconnection. An asymmetric ENSO teleconnection being the cause for the overall warming of the central, tropical Indian Ocean appears therefore unlikely. However, we suggest compiling composite records of negative and positive SST anomaly events from additional sub-fossil Indian Ocean corals to further explore the ENSO-SST teleconnection, and how it varies in cooler or warmer climatic intervals.

Author contribution: M.L. conceived the study, wrote the paper and produced all figures. M.P., L.R., T.K.W. and D.G.-S. helped with analyzing and interpreting the data. L.R. assessed the preservation of the coral samples. T.K.W., C.-C.S. and G.-J.B. helped dating the samples and with the development of the age models. M.P. acquired the funding for this project, contributed feedback and helped refine the writing.

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Data and materials availability: All methods needed to evaluate the conclusions in the paper are present in the paper and/or the supplementary material. The data plotted in all figures will be available to the public over the Paleoclimatology Branch of NOAA's National Center for Environmental Information (NCEI) (http://www.ncdc.noaa.gov/data-access/paleoclimatology-data) after the completion of the dissertation of M. Leupold.

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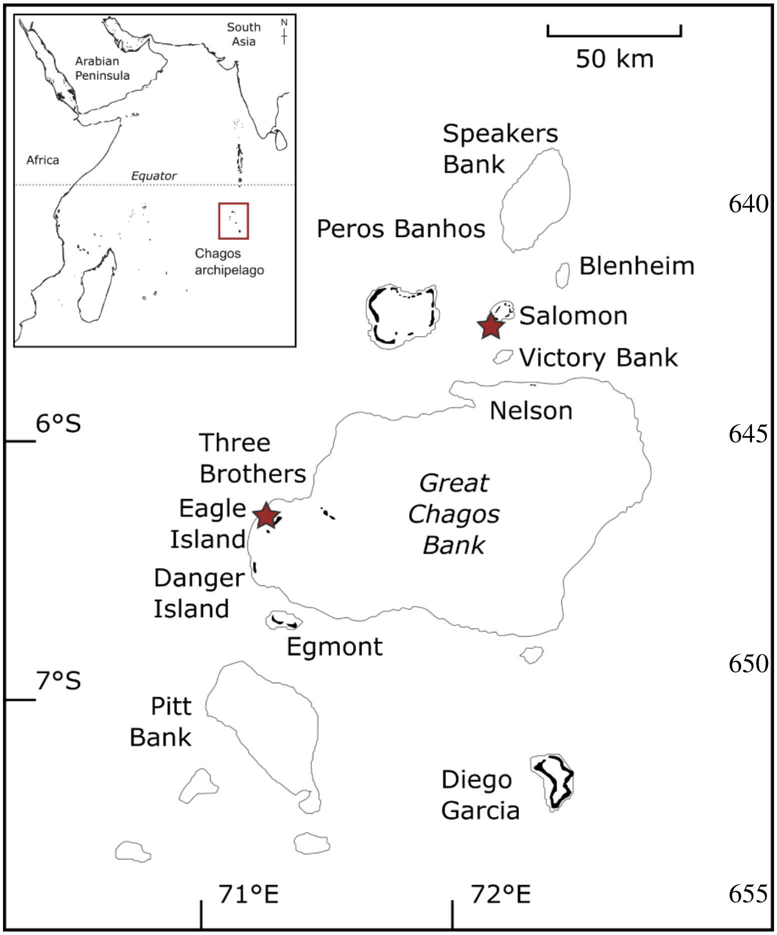

Figure 1: Location of study area and coral sample locations. The Chagos Archipelago is located in the central Indian Ocean, about 550 km south of the Maldives (map upper left). Fossil coral samples were collected on Eagle Island and on Boddam Island (Salomon atoll; red stars).

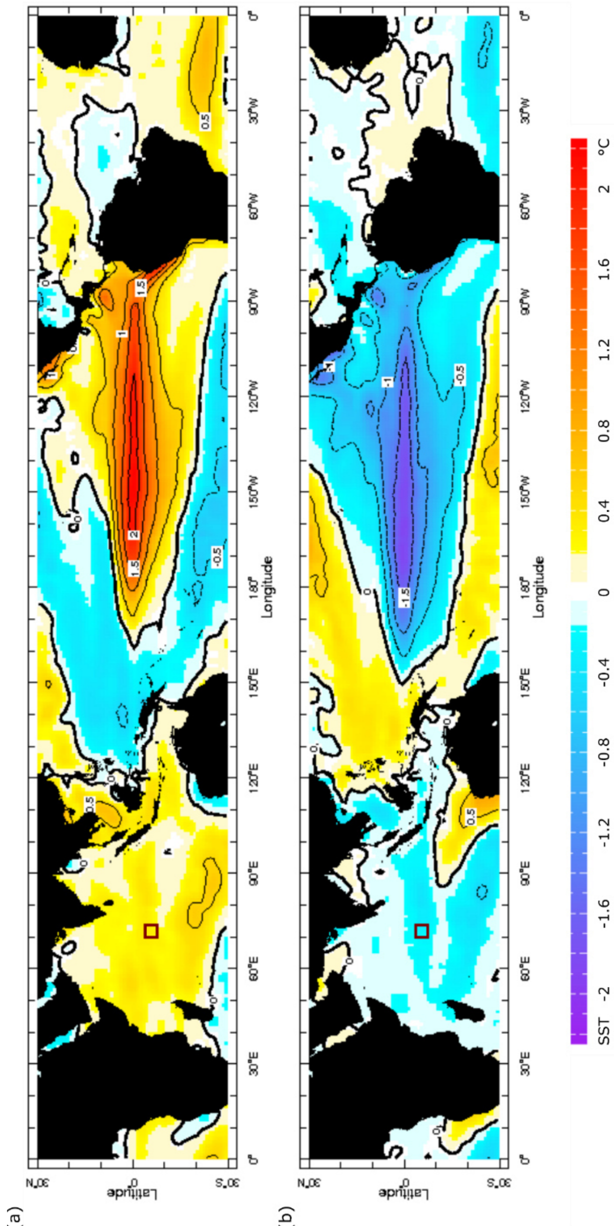

Figure 2: Composite maps of SST anomalies [°C] in the Indian and Pacific Ocean during El Niño/La Niña events. (a) El Niño SST anomalies for the period 1982 to 2016 averaged over December to February. (b) same as in (a), but for La Niña events. SST anomaly maps were computed with NOAA 'Reynolds' OI v2 SST (Reynolds et al., 2002) using the free web application Data Views of the IRI Data Library (https://iridl.ldeo.columbia.edu/). Date accessed: 17 September 2018. Red squares indicate the location of the study area. An overview of all events used for each composite map can be found in Table S1 in the supplementary material.

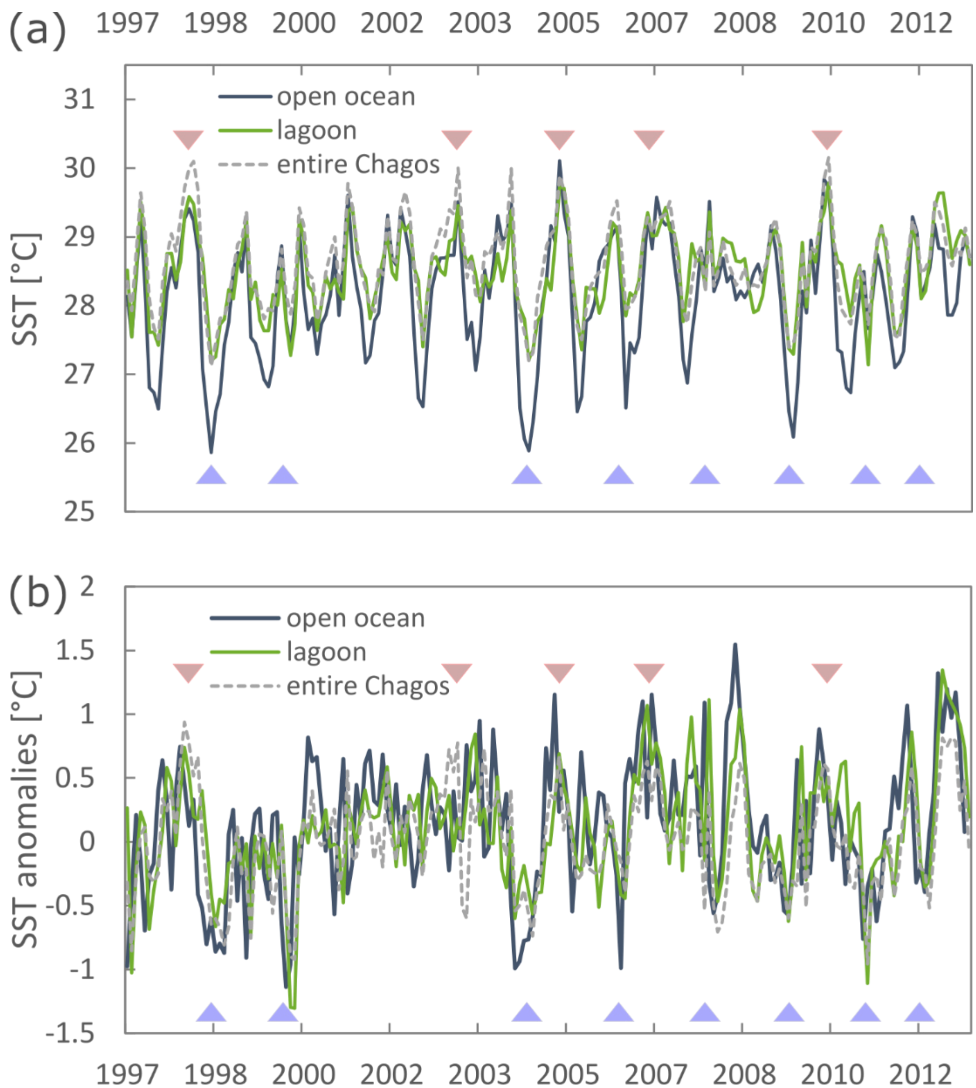

Figure 3: **Satellite SST for different settings (lagoon: green; open ocean: blue) and entire Chagos (grey; averaged over 70-74° E; 4-8° S). (a) Monthly satellite SST means and (b) satellite SST anomalies. For the open ocean and lagoon setting we used the high-resolution satellite SST product AVHRR (Casey et al., 2010) and for entire Chagos we used NOAA 'Reynolds' OI v2 SST (Reynolds et al., 2002). Arrows indicate El Niño (red) and La Niña events (blue) based on Brönnimann et al. (2007) and the Oceanic Niño Index ONI (https://www.ggweather.com/enso/oni.htm; Date accessed: 18 October 2018).**

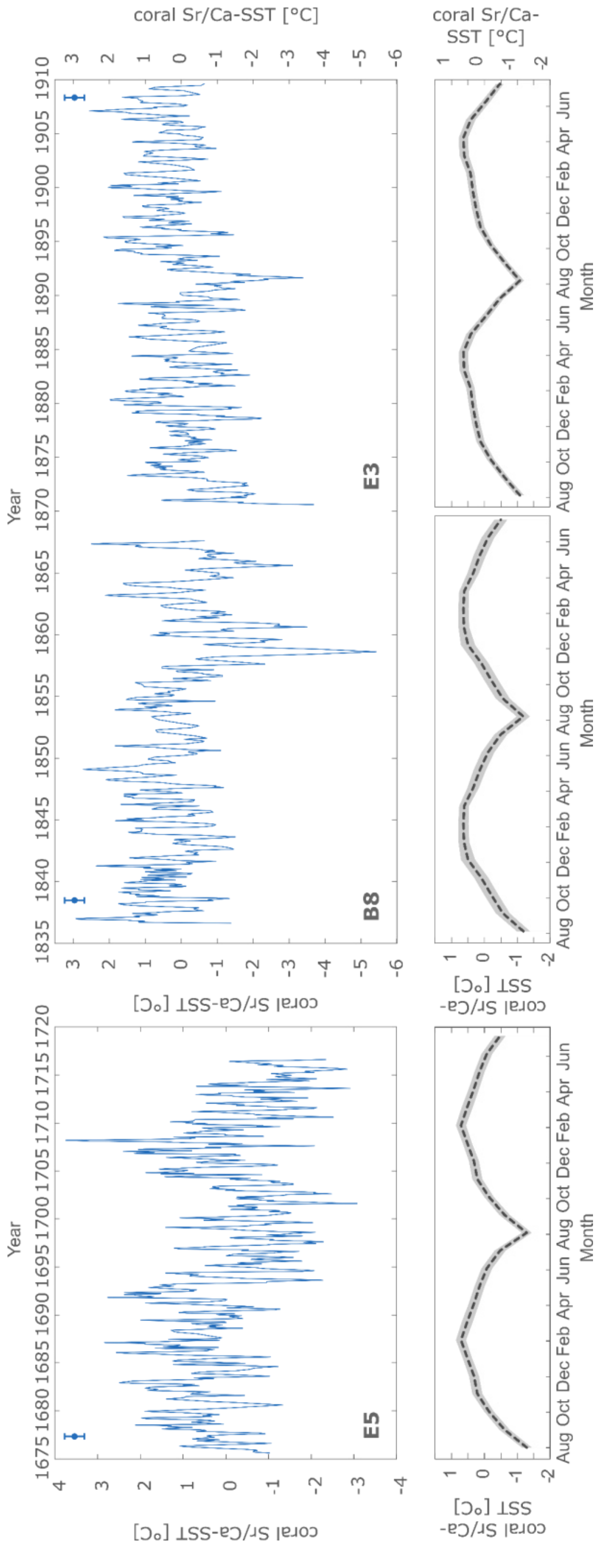
coral Sr/Ca-SST [°C]
Year
E3
B8
E5
coral Sr/Ca-SST [°C]
Month
Aug Oct Dec Feb Apr Jun Aug Oct Dec Feb Apr Jun

Figure 4: Monthly Sr/Ca records (blue lines; converted into coral Sr/Ca-SST in °C) of E5 (1675-1716), B8 (1836-1867) and E3 (1870-1909) with error bars indicating the standard deviation (±2σ) of Sr/Ca ratios from multiple measurements on the same day and on consecutive days and mean annual cycles (black lines and corresponding standard errors highlighted in gray, lower plot).

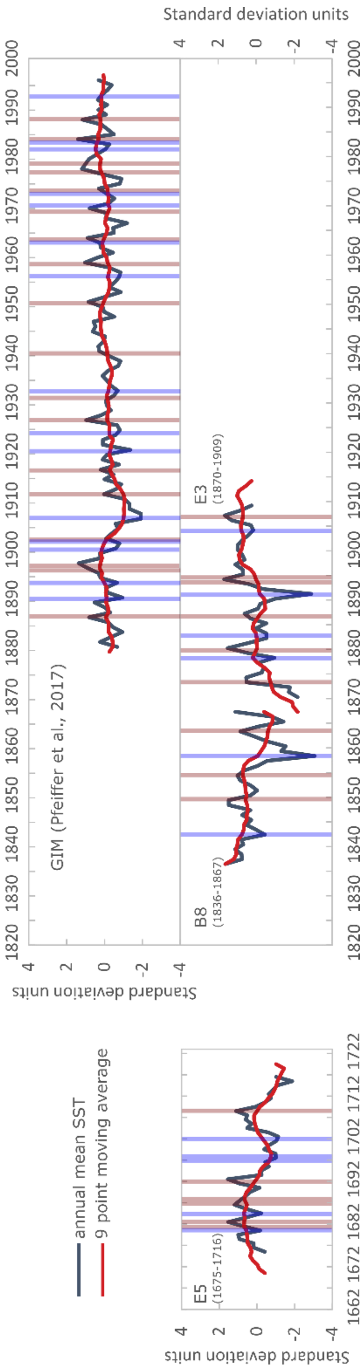

Figure 5: Annual SST anomalies for Chagos corals (this study and GIM from Pfeiffer et al. 2009, 2017) Red- (El Niño) and blue- (La Niña) shaded boxes indicate years used for the composite records (Figs. 7-9). Red thick lines are 9 point moving averages. See text Sect. 4.5 for how El Niño/La Niña events were picked.

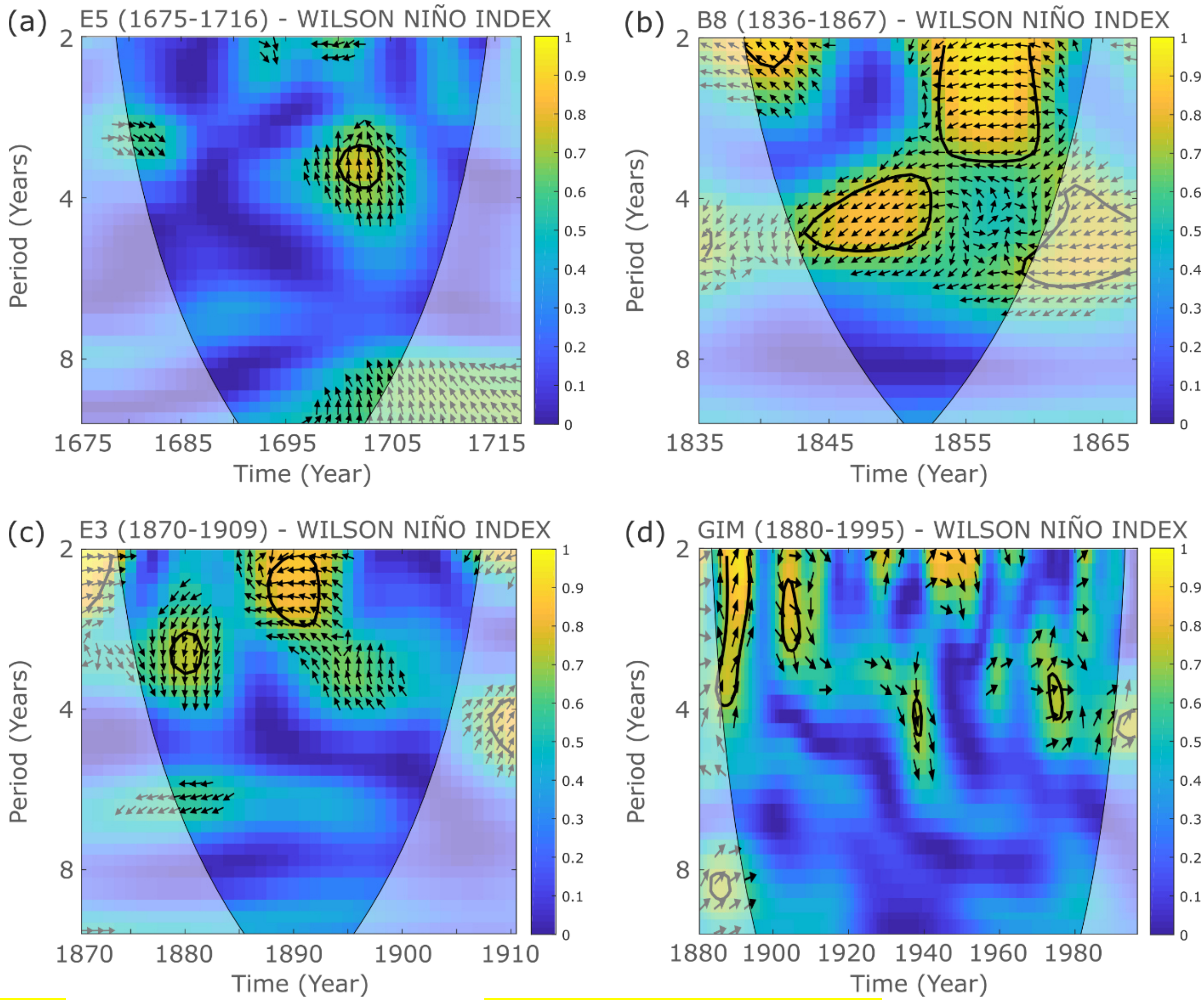

Figure 6: Wavelet coherence analysis plots for the Wilson Niño Index (Wilson et al., 2010) and Chagos coral SST of (a) E5 (1675-1716), (b) B8 (1836-1867), (c) E3 (1870-1909) and (d) GIM (1980-1995).

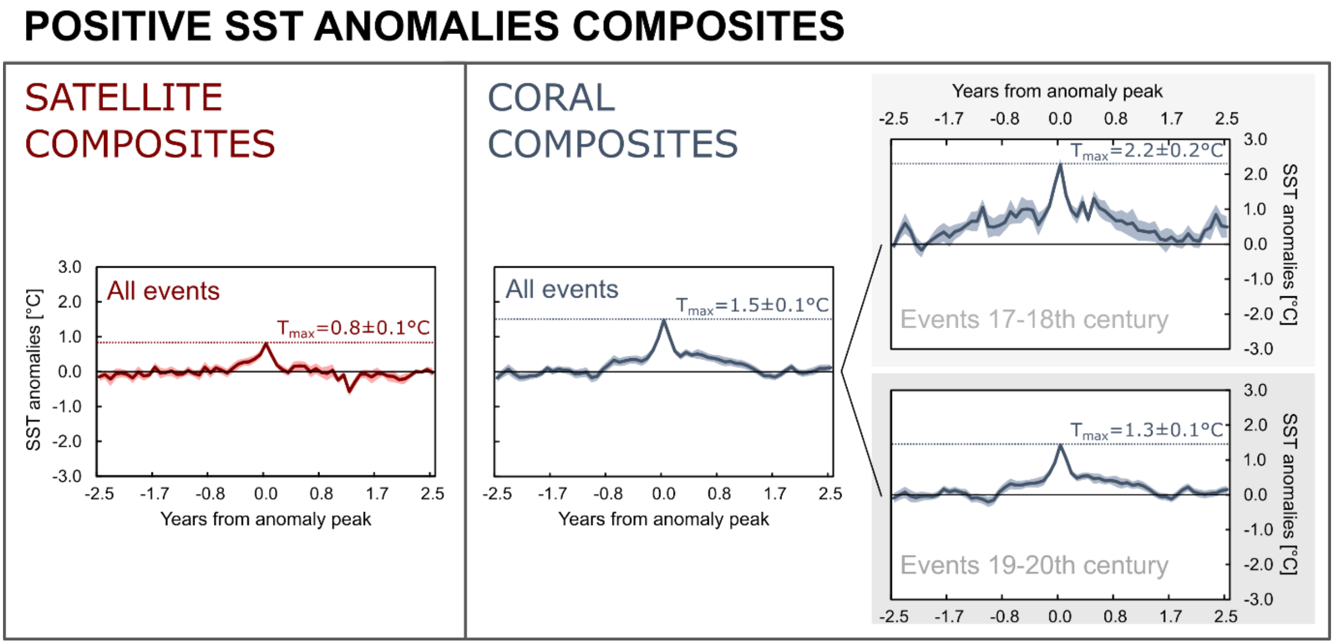

Figure 7: Positive SST anomalies (El Niño) composite records of AVHRR (left; red) and coral SST (right; blue) records. Separate composites of anomaly events during the 17-18th and 19-20th century were generated from the coral SST records. Shaded areas below and above the curves show the standard error for the mean values of the composite records. Table 4 for an overview of the events that were selected for generating the composites.

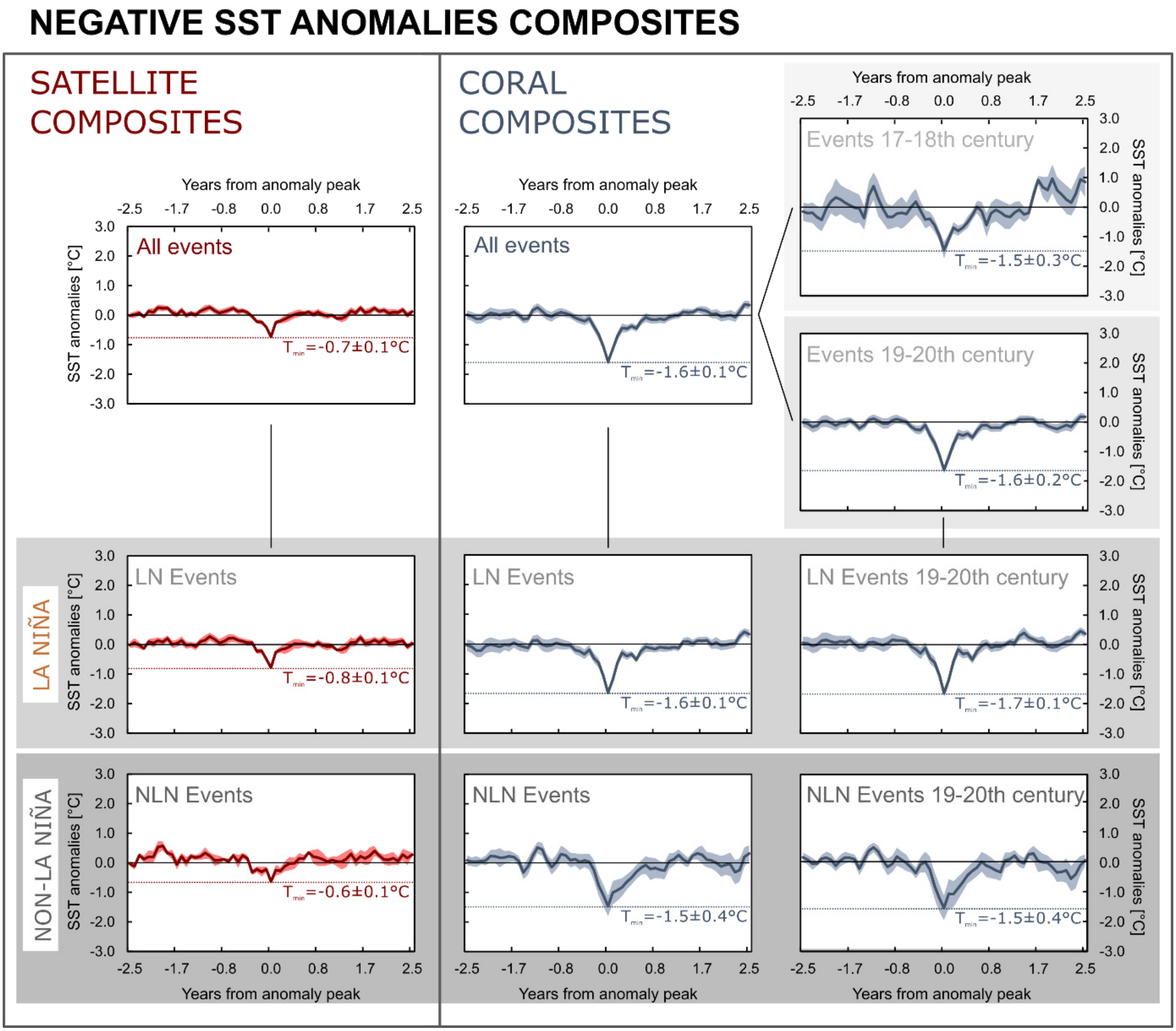

Figure 8: Negative SST anomalies (La Niña and non-La Niña) composite records of AVHRR satellite (left) and coral SST (right) records. Additionally, composites of anomaly events separated by 17-18th and 19-20th century events and by La Niña and non-La Niña events were generated. Shaded areas below and above the curves show the standard error for the mean values of the composite records. See Table 4 for an overview of the events that were selected for generating the composites.

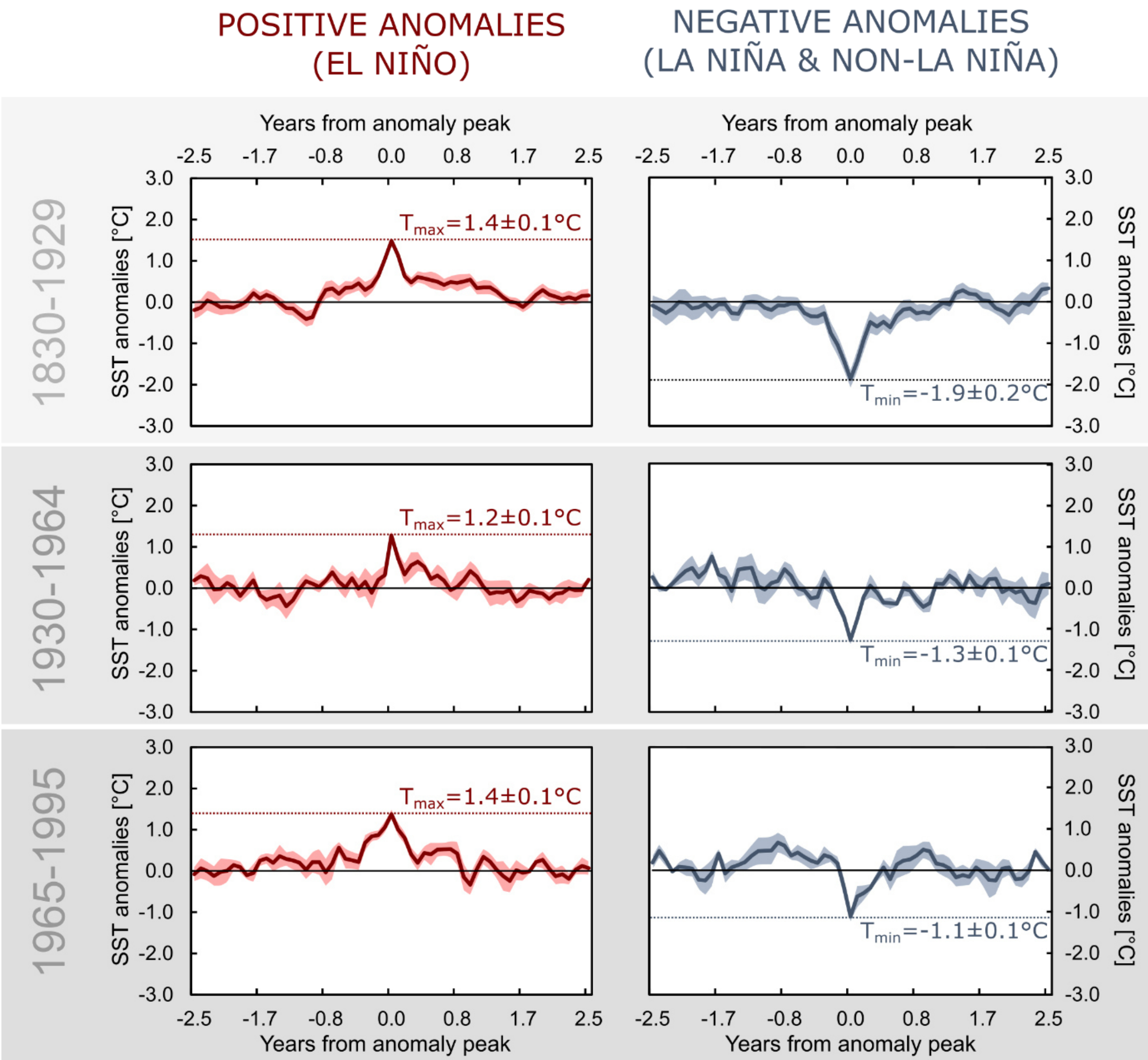

Figure 9: Positive (El Niño; left) and negative SST anomalies (La Niña and non-La Niña; right) composite records of the 19-20th century coral SST records separated by the time intervals 1830-1929 (upper row), 1930-1964 (middle row) and 1965-1995 (lower row). Shaded areas below and above the curves show the standard error for the mean values of the composites records. See Table 5 for an overview of the events that were selected for generating the composites.

Table 1: Overview of Uranium and Thorium isotopic compositions and ^{230}Th ages and corresponding years for fossil coral samples E5 (1675-1716), B8 (1836-1867) and E3 (1870-1909) measured with MC-ICPMS, Thermo Electron Neptune, at NTU. Location of measurement numbers are indicated on x-ray images in Figure S2. Chemistry was performed on March.11th, 2016 and on July 16, 2017 (Shen et al., 2003), and instrumental analysis on MC-ICP-MS (Shen et al., 2012).

Sample ID	Measurement No.	^{238}U (ppb^{a})	^{232}Th (ppt)	d^{234}U (measured^{a})	[^{230}Th/^{238}U] (activity^{c})	[^{230}Th/^{232}Th] (ppm^{d})	Age (uncorrected)	Age (corrected^{c,e})	d^{234}U$_{initial}$ (corrected^{b})	Corresponding year (BP)
E5 (1675-1716)	1st	2265,7 ± 2,3	74,1 ± 3,0	146,4 ± 1,3	0,003250 ± 0,000019	1639 ± 66	309,5 ± 1,9	308,8 ± 1,9	146,6 ± 1,3	1706 ± 1.9
	2nd	2293,9 ± 2,2	16,1 ± 1,3	145,0 ± 1,6	0,003594 ± 0,000018	8458 ± 675	342,8 ± 1,8	342,6 ± 1,8	145,2 ± 1,6	1674 ± 1.8
B8 (1836-1867)	1st	2212,7 ± 2,5	37,1 ± 4,1	144,1 ± 1,5	0,001872 ± 0,000023	1840 ± 203	178,5 ± 2,2	178,1 ± 2,2	144,2 ± 1,5	1838 ± 2.2
	2nd	2386,1 ± 2,1	515,4 ± 1,4	146,2 ± 1,3	0,001650 ± 0,000029	126 ± 2	157,1 ± 2,8	152,1 ± 3,7	146,2 ± 1,3	1865 ± 3.7
E3 (1870-1909)	1st	2551,9 ± 2,5	56,7 ± 3,9	145,4 ± 1,3	0,001194 ± 0,000025	886 ± 64	113,8 ± 2,4	113,3 ± 2,4	145,4 ± 1,3	1903 ± 2.4
	2nd	2694 ± 2,8	643 ± 2	144,7 ± 1,7	0,0015 ± 0,00002	106 ± 1	146 ± 2	141 ± 3,2	145 ± 1,7	1876 ± 3.2

Analytical errors are 2σ of the mean.
^{a}[^{238}U] = [^{235}U] x 137.818 (±0.65‰) (Hiess et al., 2012); $\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$.
$^{b}\delta^{234}$Uinitial corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{\lambda_{234} * T}$, and T is corrected age.
$^{c}[^{230}Th/^{238}U]_{activity} = 1 - e^{-\lambda_{230} T} + (\delta^{234}U_{measured}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](\lambda - e^{-(\lambda_{230} - \lambda_{234}) T})$, where T is the age.
^{d}The degree of detrital ^{230}Th contamination is indicated by the [^{230}Th/^{232}Th] atomic ratio instead of the activity ratio.
^{e}Age corrections, relative to chemistry date, for samples were calculated using an estimated atomic ^{230}Th/^{232}Th ratio of 4 ± 2 ppm. Those are the values for a material at secular equilibrium, with the crustal ^{232}Th/^{238}U value of 3.8. The errors are arbitrarily assumed to be 50%.

Table 2: Statistical overview for raw Sr/Ca data.

Sample	Amount subsamples	Sr/Ca [mmol/mol]						median RSD [%]
		Mean	Median	Std dev	Min	Max	Range	
E5 (1675-1716)	472	8.96	8.96	0.07	8.73	9.14	0.410	0.076
B8 (1836-1867)	375	9.02	9.02	0.07	8.85	9.36	0.506	0.075
E3 (1870-1909)	415	8.95	8.95	0.06	8.79	9.17	0.376	0.074

Table 3: Statistical overview for mean annual cycle data of the coral Sr/Ca-SST [°C] records.

Sample	Max	Min	Amplitude	Mean	SD	P-value of t-test (two-tailed)		
						E5 (1675-1716) vs.	B8 (1836-1867) vs.	E3 (1870-1909) vs.
E5 (1675-1716)	0.70	-1.29	1.99	0.0026	0.5459		0.9979	0.9991
B8 (1836-1867)	0.61	-1.21	1.82	0.0033	0.5450	0.9979		0.9969

E3 (1870-1909)	0.60	-1.11	1.71		0.0024	0.5089	0.9991	0.9969	

***Note*. SD is the standard deviation.**

			Years with events	Number of events	Records used
Composite					
Postive SST anomalies	Coral Composites	all events	1679, 1682, 1686, 1687, 1691, 1708, 1849, 1853, 1863, 1873, 1879, 1881, 1886 (2x), 1889, 1894, 1895, 1896, 1897, 1902, 1907, 1911, 1916, 1926, 1932, 1940, 1951, 1958, 1963, 1969, 1973, 1977, 1979, 1983, 1987	35	E5 (1675-1716), B8 (1836-1867), E3 (1870-1909), GIM (1880-1995)
		17-18th century	1679, 1682, 1686, 1687, 1691, 1708	6	E5 (1675-1716)
		19-20th century	1849, 1853, 1863, 1873, 1879, 1881, 1886 (2x), 1889, 1894, 1895, 1896, 1897, 1902, 1907, 1911, 1916, 1926, 1932, 1940, 1951, 1958, 1963, 1969, 1973, 1977, 1979, 1983, 1987	29	B8 (1836-1867), E3 (1870-1909), GIM (1880-1995)
	Satellite Composite	all events	1983, 1987, 1988, 1998, 2003, 2005, 2007, 2015, 2016	9	AVHRR SST (1981-2018)
Negative SST anomalies	Coral Composites	all events	1680, 1684, 1697, 1698, 1702, 1846, 1858, 1860, 1865, 1872, 1883, 1890, 1891, 1893, 1895, 1900, 1902, 1903, 1906, 1920, 1924, 1932, 1947, 1952, 1956, 1964, 1970, 1974, 1982, 1984, 1994	31 (22 LN, 9 NLN)	E5 (1675-1716), B8 (1836-1867), E3 (1870-1909), GIM (1880-1995)
		17-18th century	1680, 1684, 1697, 1698, 1702	5	E5 (1675-1716)
		19-20th century	1846, 1858, 1860, 1865, 1872, 1883, 1890, 1891, 1893, 1895, 1900, 1902, 1903, 1906, 1920, 1924, 1932, 1947, 1952, 1956, 1964, 1970, 1974, 1982, 1984, 1994	26 (19 LN, 7 NLN)	B8 (1836-1867), E3 (1870-1909), GIM (1880-1995)
	Satellite Composite	all events	1984, 1989, 1989, 1992, 1995, 1996, 1998, 2000, 2004, 2008, 2011, 2012, 2014, 2017	14 (10 LN, 4 NLN)	AVHRR SST (1981-2018)

Table 4: Positive (El Niño) and negative (La Niña and non-La Niña) SST anomaly events picked for generating coral and satellite composite records shown in Figure 7 and Figure 8.

19-20th century Coral Composite	Period	Years with events	Number of events	Records used
Postive SST anomalies	1830-1929	1849, 1853, 1863, 1873, 1879, 1981, 1886 (2x), 1889, 1894, 1895, 1896, 1897, 1902, 1907, 1911, 1916, 1926	18	B8 (1836-1867), E3 (1870-1909), GIM (1880-1995)
	1930-1964	1932, 1940, 1951, 1958, 1963	5	GIM (1880-1995)
	1965-1995	1969, 1973, 1977, 1979, 1983, 1987	6	GIM (1880-1995)
Negative SST anomalies	1830-1929	1846, 1858, 1860, 1865, 1872, 1883, 1890, 1891, 1893, 1895, 1900, 1902, 1903, 1906, 1920, 1924	16	B8 (1836-1867), E3 (1870-1909), GIM (1880-1995)
	1930-1964	1932, 1947, 1952, 1956, 1964	5	GIM (1880-1995)
	1965-1995	1970, 1974, 1982, 1984, 1994	5	GIM (1880-1995)

Table 5: 19-20th century (divided into three periods) positive (El Niño) and negative (La Niña and non-La Niña) SST anomaly events picked for generating coral composite records shown in Figure 9.

	Positive SST Anomalies						Negative SST Anomalies			
	Events in Records		Published ENSO events				Events in Records		Published ENSO events	
			Quinn (1993)		Brönnimann et al. (2007)				Brönnimann et al. (2007)	
	Years	Numbers of events	Years of very strong (VS), strong (S), medium (M) and weak (W) events	Numbers of events	Years of strong events	Numbers of events	Years	Numbers of events	Years of strong events	Numbers of events
E5 (1675-1716)	1678/79, 1682/83, 1685/86, 1686/87, 1691/92, 1707/08	6	1681 (S), 1684 (M+), 1687-88 (S+), 1692-93 (S), 1696-97 (M+), 1701 (S+), 1707-09 (M/S), 1715-16 (S)	8	1674, 1675, 1677, 1681, 1682, 1691, 1702	7	1680, 1683/84, 1697, 1697/98, 1702	5	1676, 1678, 1698, 1704	4
B8 (1836-1867)	1848/49, 1853/54, 1862/63	3	1837 (M+), 1844-46 (M/S+), 1850 (M), 1852 (M), 1854 (M), 1857-58 (M), 1860 (M), 1862 (M-), 1864 (S), 1866 (M+), 1867-68 (M+)	11	1833, 1846, 1852, 1856, 1869	5	1845/46, 1858, 1860/61, 1864/65	4	1842, 1847, 1863	3
E3 (1870-1909)	1872/73, 1879/80, 1885/86, 1893/94, 1894/95, 1906/07	6	1871 (S+), 1874 (M), 1877-78 (VS), 1880 (M), 1884 (S+), 1887-89 (M+), 1891 (VS), 1897 (M+), 1899-1900 (S), 1902 (M+), 1904-05 (M-), 1907 (M)	12	1869, 1877, 1878, 1889, 1897, 1900, 1903, 1906, 1912	9	1872, 1882/83, 1891, 1895/96, 1903/04	5	1872, 1887, 1890, 1893, 1904, 1910	6
GIM (1880-1995)*	1880/81, 1885/86, 1888/89, 1896/97, 1897, 1902, 1911/12, 1916/17, 1925/26, 1931/32, 1939/40, 1950/51, 1957/58, 1962/63, 1969/70, 1972/73, 1977/78, 1978/79, 1982/83, 1986/87	20	1880 (M), 1884 (S+), 1887-89 (M-/M+), 1891 (VS), 1897 (M+), 1899-90 (S), 1902 (M+), 1904-05 (M-), 1907 (M), 1910 (M+), 1911-12 (S), 1914-15 (M+), 1917 (S), 1923 (M), 1925-26 (VS), 1930-31 (M), 1932 (S), 1939 (M+), 1940-41 (S), 1943 (M+), 1951 (M-), 1953 (M+), 1957-58 (S), 1965 (M+), 1969 (M-), 1972-73 (S), 1976 (M), 1978-79 (W), 1982-83 (VS), 1987 (M), 1991-92 (M), 1994-95 (M-)	32	1878, 1889, 1897, 1900, 1903, 1906, 1912, 1915, 1919, 1926, 1931, 1940, 1941, 1952, 1958, 1966, 1973, 1977, 1983, 1987, 1992	21	1889/90, 1893, 1899/00, 1901/02, 1906, 1919/20, 1924, 1931/32, 1947, 1956, 1951/52, 1964, 1970, 1973/74, 1982, 1983/84, 1993/94	17	1887, 1890, 1893, 1904, 1910, 1917, 1925, 1934, 1943, 1950, 1956, 1968, 1971, 1974, 1976, 1985, 1989	17
AVHRR*	1982/83, 1986/87, 1987/88, 1997/98, 2002/03, 2004/05, 2006/07, 2014/15, 2015/16	9	1982/83 (VS), 1986/87 (M), 1987/88 (S), 1991/92 (S), 1994/95 (M), 1997/98 (VS), 2002/03 (M), 2004/05 (W), 2006/07 (W), 2009/10 (M), 2014/15 (W), 2015/16 (VS)	12	/	/	1984/85, 1989, 1989, 1992, 1995, 1996/97, 1998/99, 1999/00, 2004, 2007/08, 2010/11, 2011/12, 2014, 2016/17	14	1983/84 (W), 1984/85 (W), 1988/89 (S), 1992, 1995/96 (M), 1996/97, 1998/99 (S), 1999/00 (S), 2000/01 (W), 2004, 2005/06 (W), 2007/08 (S), 2008/09 (W), 2010/11 (S), 2011/12 (M), 2014, 2016/17 (W), 2017/18 (W)	18

* Note: Recent events (from 1980 on) were additionally picked using events listed on this website: https://www.ggweather.com/enso/oni.htm (Date accessed: 18 October 2018)

Table 6: Overview of all events found in the coral Sr/Ca records and of El Niño/La Niña events of the corresponding time periods listed in publications. Events in coral records were matched with published events in consideration of age model uncertainties of each coral record.

Introduction. This file includes supplementary methods, pictures of sampling locations (Fig. S1), x-ray images of the coral samples (Fig. S2), photomicrographs of the coral samples (Figs. S3-S5), power spectrum analysis plots of non-detrended coral SST anomalies (Fig. S6), plots with Sr/Ca-SST anomalies and anomalies after detrending (Fig. S7), and SSA plots (Figs. S8-S10) and power spectrum analysis plots of detrended coral SST (Fig. S11) including text descriptions. Two additional tables giving the years of El Niño/La Niña events used for the composite maps (Table S1) and the linear regression results between the coral SST records and the Wilson Niño Index (Table S2) are also part of this supplementary material.

1 Supplementary Methods

Indices

We use Niño 3.4 SST anomalies taken from NOAA ERSSTv5 (Huang et al. 2017) for power spectrum analysis (Fig. S11). These have been interpolated from sparse observational data and extend back until 1870.

Statistics

Power spectra analysis was performed twice using the spectral analysis function REDFIT (Welch window) of the open source software *PAST* (version 3.25; Hammer et al., 2001). One run was performed with the time series before detrending them, one run after detrending. Every time series was detrended using the softwares *breakfit* (Mudelsee, 2009) or *rampfit* (Mudelsee, 2000), respectively (Fig. S7).

Singular spectrum analysis (SSA) (Vautard and Ghil, 1989) were generated using the *MATLAB* (version R2019b) software toolboxes by Groth and Ghil (2015).

2 Table with years of events that were used in the composite maps (Fig. 2 in main document)

Event years	
El Niño	La Niña
1982/83	1984/85
1986/87	1988/89
1987/88	1995/95
1991/92	1998/99
1994/95	1999/00
1997/98	2007/08
2002/03	2010/11
2009/10	2011/12
2015/16	

Table S1: El Niño and La Niña event years used for the composite maps. Between 1982 and 2016, 9 El Niño events and 8 La Niña events occurred. Temperature anomalies from December to February were averaged for each event.

3 Pictures of coral sample sites

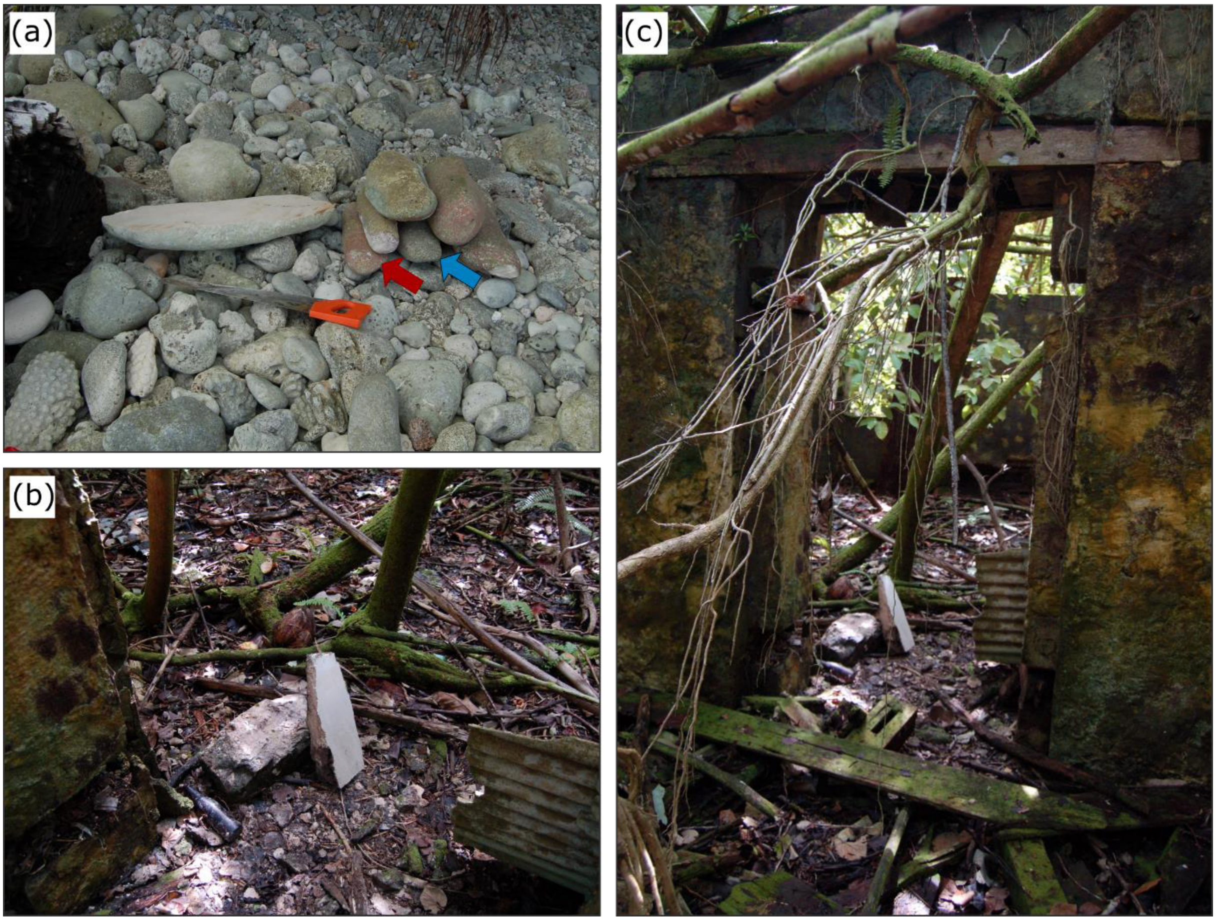

Figure S1: Pictures of coral sample sites. (a) Boulder beach at Eagle Island where the samples E5 (1675-1716; blue arrow) and E3 (1870-1909; red arrow) were collected. (b) and (c) a derelict building at Boddam Island from which the sample B8 (1836-1867) was collected.

4 X-ray images

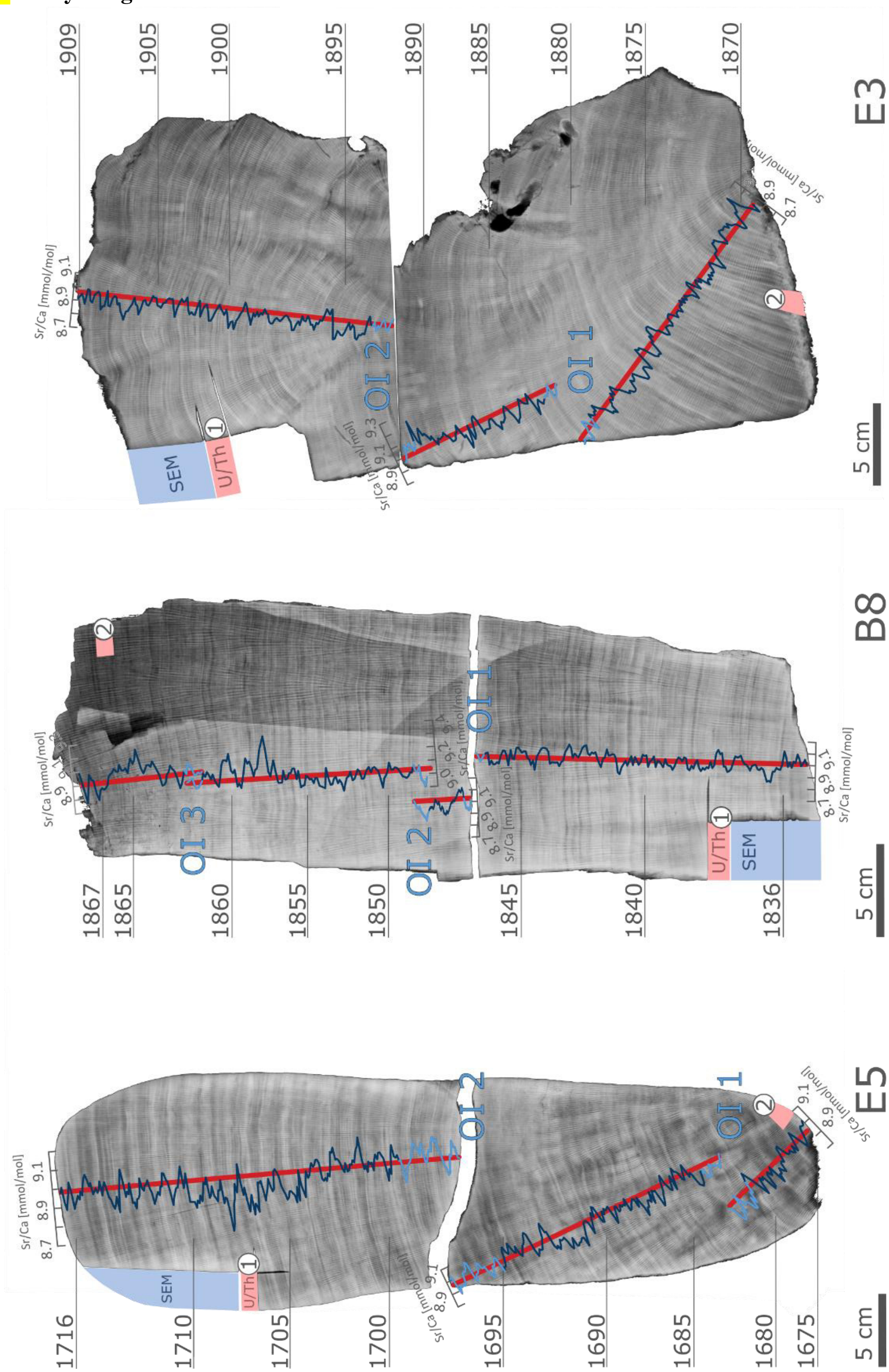

Figure S2: X-Ray images of coral samples analyzed in this study with raw Sr/Ca data (dark blue lines). Age models were interpreted using two U/Th measurements from each sample (sampling points for U/Th dating are indicated with circled numbers and light red-shaded areas; for determined ages see Table 1). Red lines indicate subsampling paths. Blue-shaded areas indicate sampling locations for subsamples used for Scanning Electron Microscopy (SEM). Please note that the slab of sample B8 is uneven as the slab was too brittle to polish out saw cuttings from field work and these are still seen on the x-ray image. Note the even growth patterns of all samples.

5 Thin section and SEM analysis images

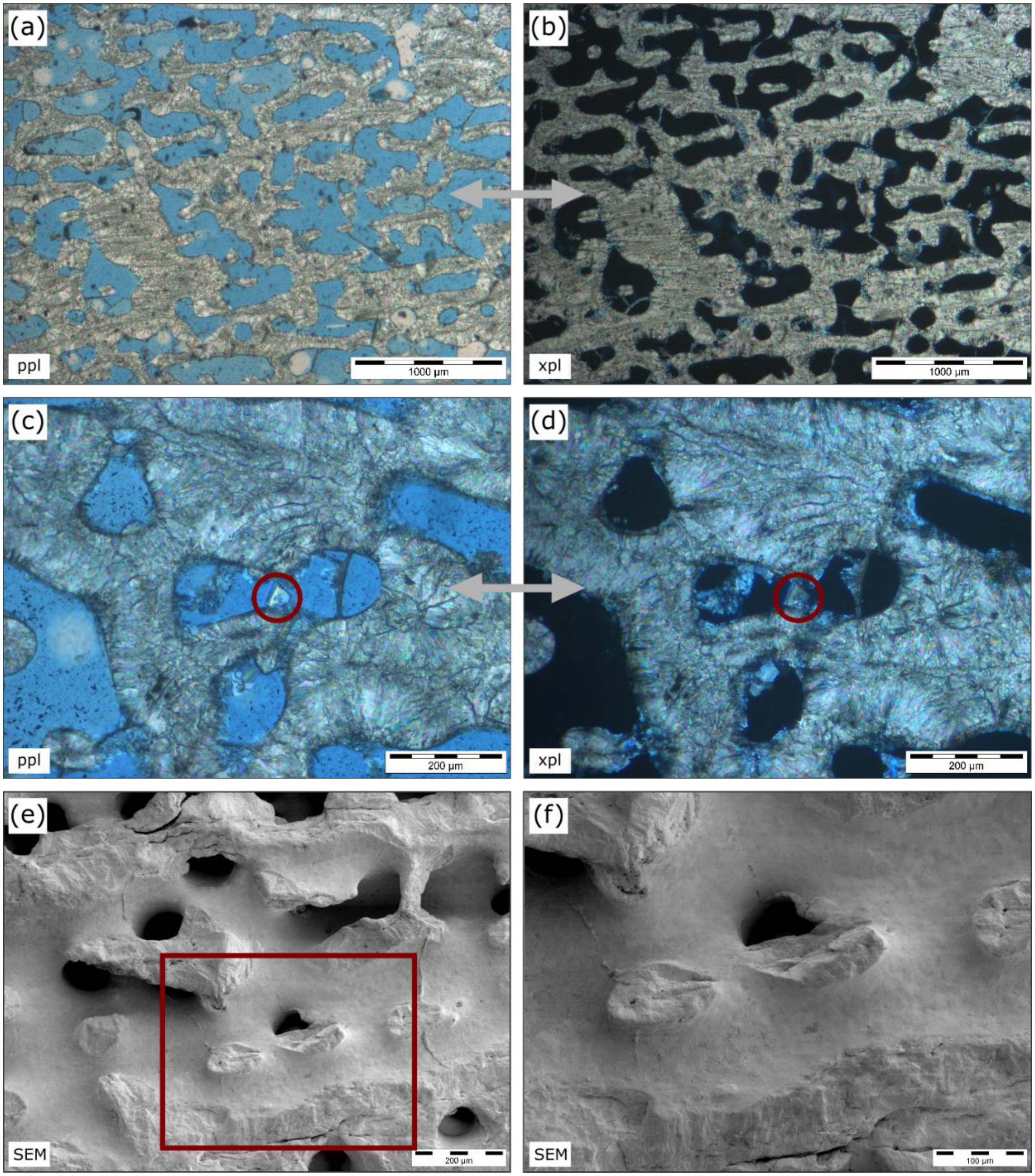

Figure S3: Photomicrographs of coral sample E5 (1675-1716). Double arrows indicate corresponding photomicrographs. (a) PPL and (b) XPL overview photomicrograph of the coral skeleton. (c) PPL and (d) XPL photomicrograph of higher resolution where minor amounts of secondary calcite cement is visible (red circle). (e) SEM overview and (f) SEM detail image of (e) where only trace amounts of sugary cements can be found.

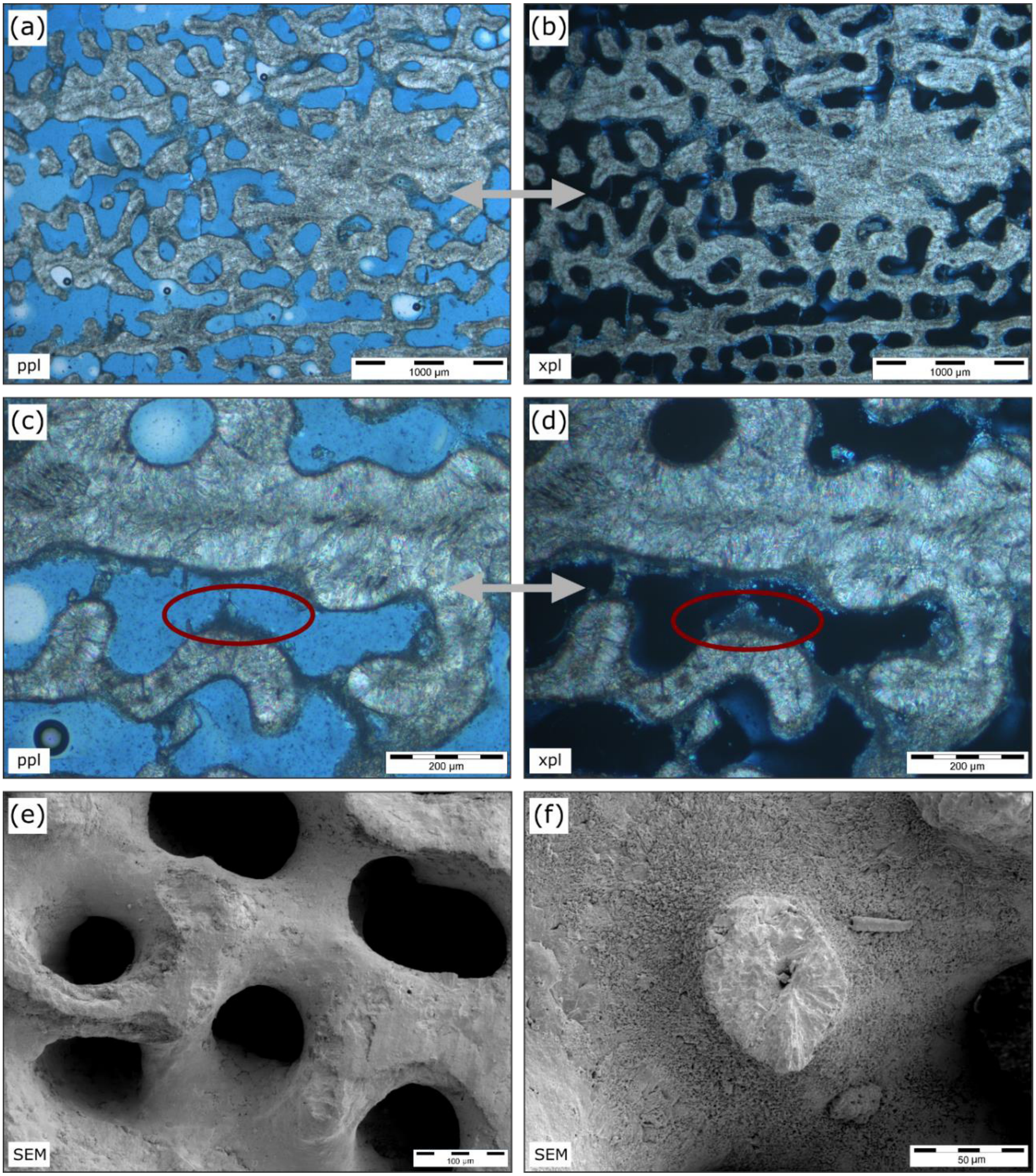

Figure S4: Photomicrographs of coral sample B8 (1836-1867). Double arrows indicate corresponding photomicrographs. (a) PPL and (b) XPL overview photomicrograph of the coral skeleton. (c) PPL and (d) XPL photomicrograph of higher resolution where small amounts of secondary aragonite cement is visible (red oval). (e) SEM overview image and (f) SEM detail image of B8 (1836-1867). Small amounts of sugary aragonitic cement can be seen.

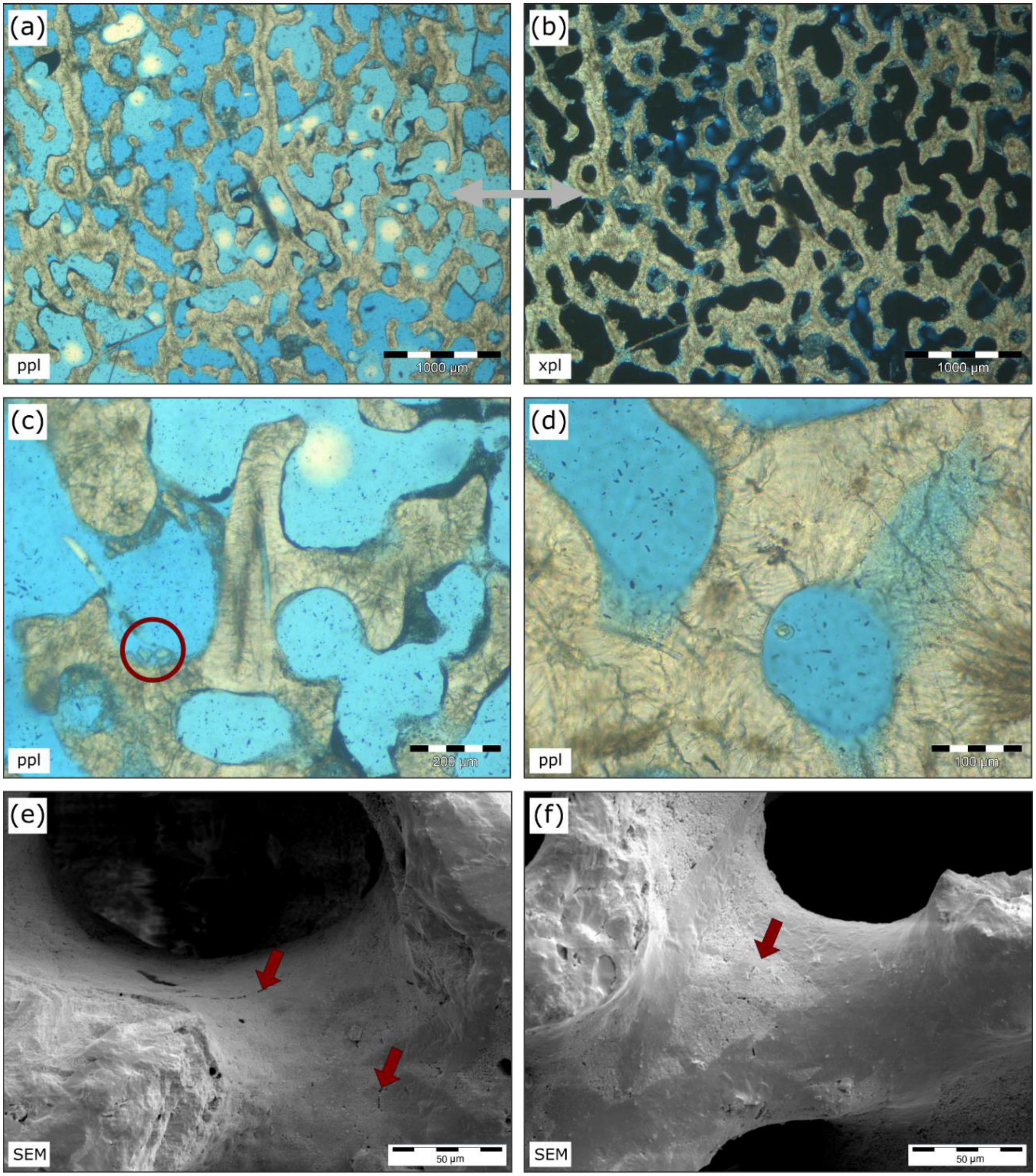

Figure S5: Photomicrographs of coral sample E3 (1870-1909). Double arrows indicate corresponding photomicrographs. (a) PPL and (b) XPL overview photomicrograph of the coral skeleton. (c) PPL photomicrograph of higher resolution where small fragments of aragonite are found (red circle). (d) PPL microphotograph of higher resolution with no signs of diagenesis. SEM images showing (e) microborings (red arrows) and (f) areas which appear brighter due to dissolution.

6 Seasonal cycles inferred from Singular Spectrum Analysis

Singular spectrum analysis (SSA) of the coral records with seasonal cycles reveal large interannual to decadal SST variabilities during both the 17-18th century and 19-20th century (not shown). The reconstructed components 2 and 3 (RC2, RC3) produced by SSA describe seasonal amplitudes for all samples and explain 28% (E5), 26% (B8), 32% (E3) of the coral Sr/Ca-SST variance. Decadal variabilities are larger during the 17-18th century compared to the 19-20th century. The first reconstructed component (RC1) of E5 with seasonal cycles explains 48% of the coral Sr/Ca-SST variance and describes a periodicity of around 18 years. The coral records covering the 19-20th century do not show a strong decadal component in SSA. Instead, RC1 explains 49% (B8) and 39% (E3) of the coral Sr/Ca-SST variance and describes a periodicity of around 7 years, which can be interpreted as ENSO periodicity.

The SSA results were validated by power spectrum analysis of bimonthly coral SST anomalies, which were not detrended (Fig. S7). For this analysis, the coral record GIM (Pfeiffer et al., 2017) was included, which extends from 1880-1995. Power spectrum analysis of E5 (Fig. S7a) shows a low-frequency band corresponding to a periodicity of 18-19 years, identical to RC1 of the SSA. In addition, RC2 describing an ENSO periodicity of 4-5 years is confirmed by the second highest low-frequency band in power spectrum analysis of E5. The power spectrum analysis of the corals covering the 19-20th century (B8 and E3) confirms their SSA results, as well (Figs. S7b & c). It shows high power on the low-frequency (5-6 years for B8; 6-7 years for E3) band, which was also described by the first reconstructed components in SSA. Power spectrum analysis for GIM (Fig. S7d) reveals high power on the ENSO band (4-5 years and 8 years) and the highest power at the decadal frequencies (26 years).

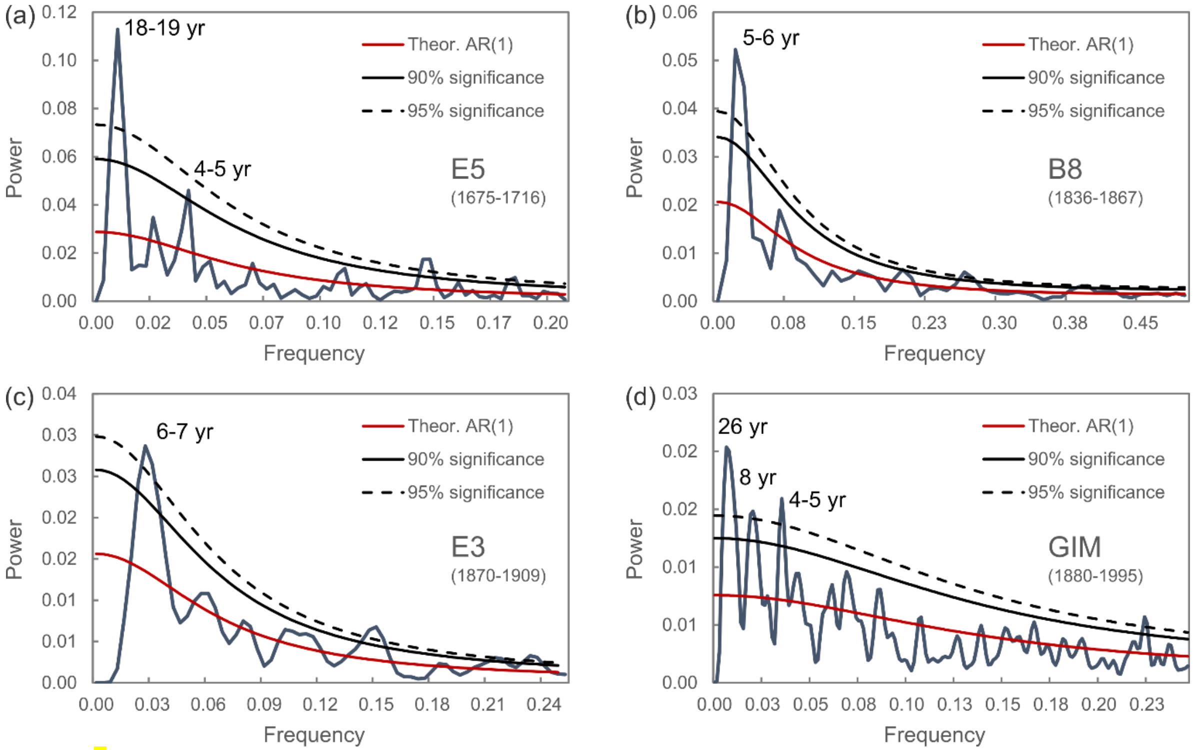

Figure S6: Power spectrum analysis of each Chagos coral bimonthly anomaly series.

7 Detrending of coral SST records

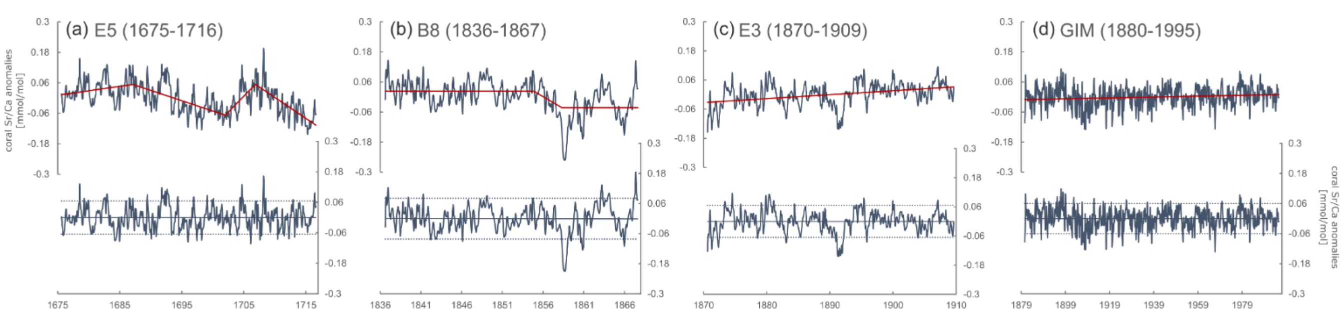

Figure S7: Sr/Ca-SST anomalies with calculated trend lines (red lines; upper plot) and anomalies after detrending (lower plot; with plotted 1.5x of the standard deviation as dashed lines) for the coral records (a) E5 (1675-1716), (b) B8 (1836-1867), (c) E3 (1870-1909) and (d) GIM (1880-1995).

8 Interannual SST variability inferred from Singular Spectrum Analysis

The spectral results of the coral records with seasonal cycles were validated by singular spectrum analysis (SSA) of coral SST anomalies records and power spectrum analysis, to reveal stronger patterns of variance when seasonal cycles were subtracted out (Figs. S8-S11). During the 17-18th century, the coral record shows a periodicity of 18 years in RC1, which explains 47% of the coral Sr/Ca-SST variance (Fig. S8). The second reconstructed component (RC2; Fig. S8) of E5 (1675-1716) explains 14% of the coral Sr/Ca-SST variance and describes an ENSO periodicity of 4-5 years. During the 19-20th century, the pattern of variance describing the ENSO periodicity in the coral records are found in two to three reconstructed components: For B8 (1836-1867), RC2 and RC3 describe an ENSO periodicity of 5-8 years with, in total, 62% of the corals Sr/Ca-SST variability (Fig. S9). For E3 (1870-1909) it is even higher with RC1-3 explaining 65% of the coral Sr/Ca-SST variance. Those three components describe a characteristic ENSO periodicity of 3-8 years (Fig. S10).

Power spectra of detrended coral SST time series all show the typical ENSO periodicity between 3 and 8 years (Fig. S11a-d). Those periodicities can also be found in the power spectra of the Niño3.4 indices (Fig. S11e & f). Even after detrending, the power spectrum of the GIM coral SST record still shows the highest power at low-frequencies, which translates to a period of 21-22 years.

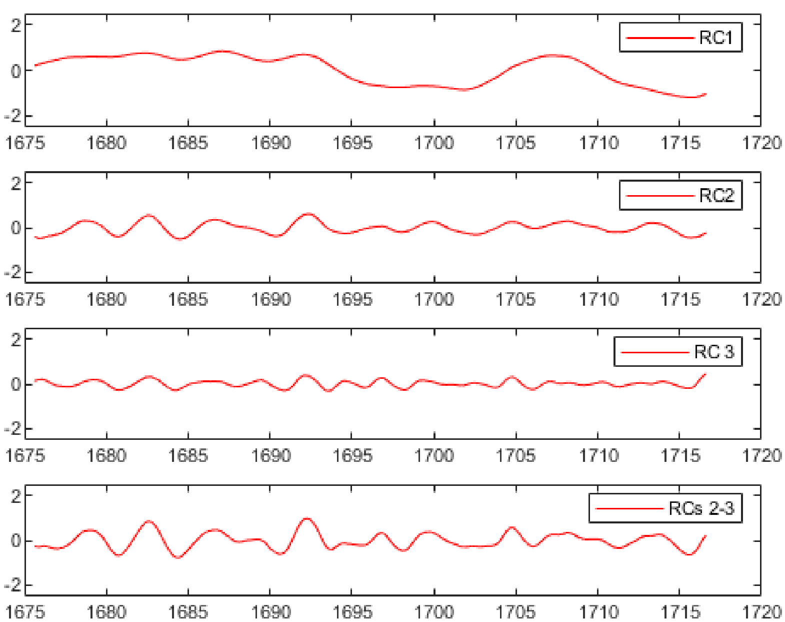

Figure S8: Reconstructed components from Singular Spectrum Analysis of E5 (1675-1716) Sr/Ca monthly anomalies. First reconstructed component (RC1) describes a periodicity of 18 years. RC2 and RC3 describe typical ENSO periodicities.

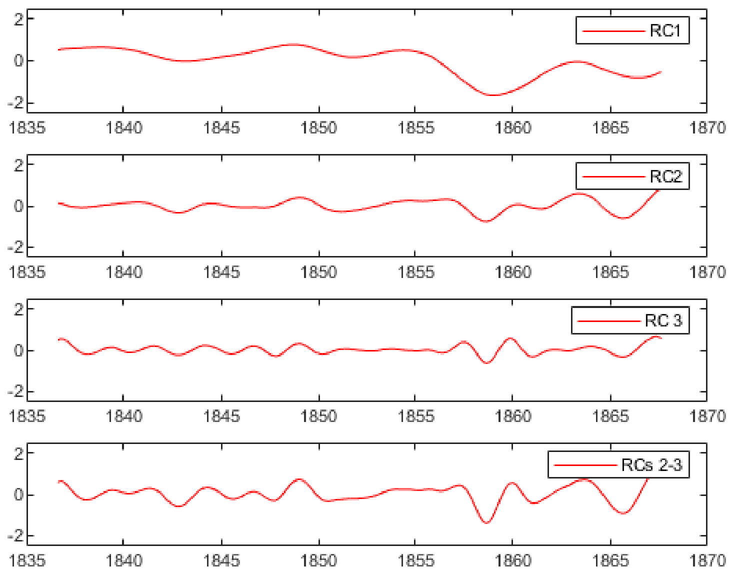

Figure S9: As Figure S8, but for coral Sr/Ca record of B8 (1836-1867).

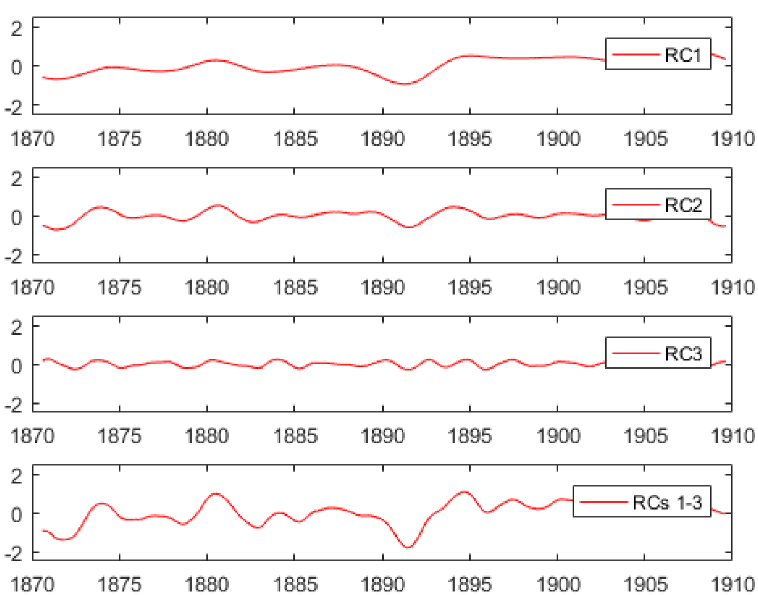

Figure S10: As Figures S8 and S9, but for coral Sr/Ca record of E3 (1870-1909) and ENSO periodicities are described by all shown reconstructed components RC1-3.

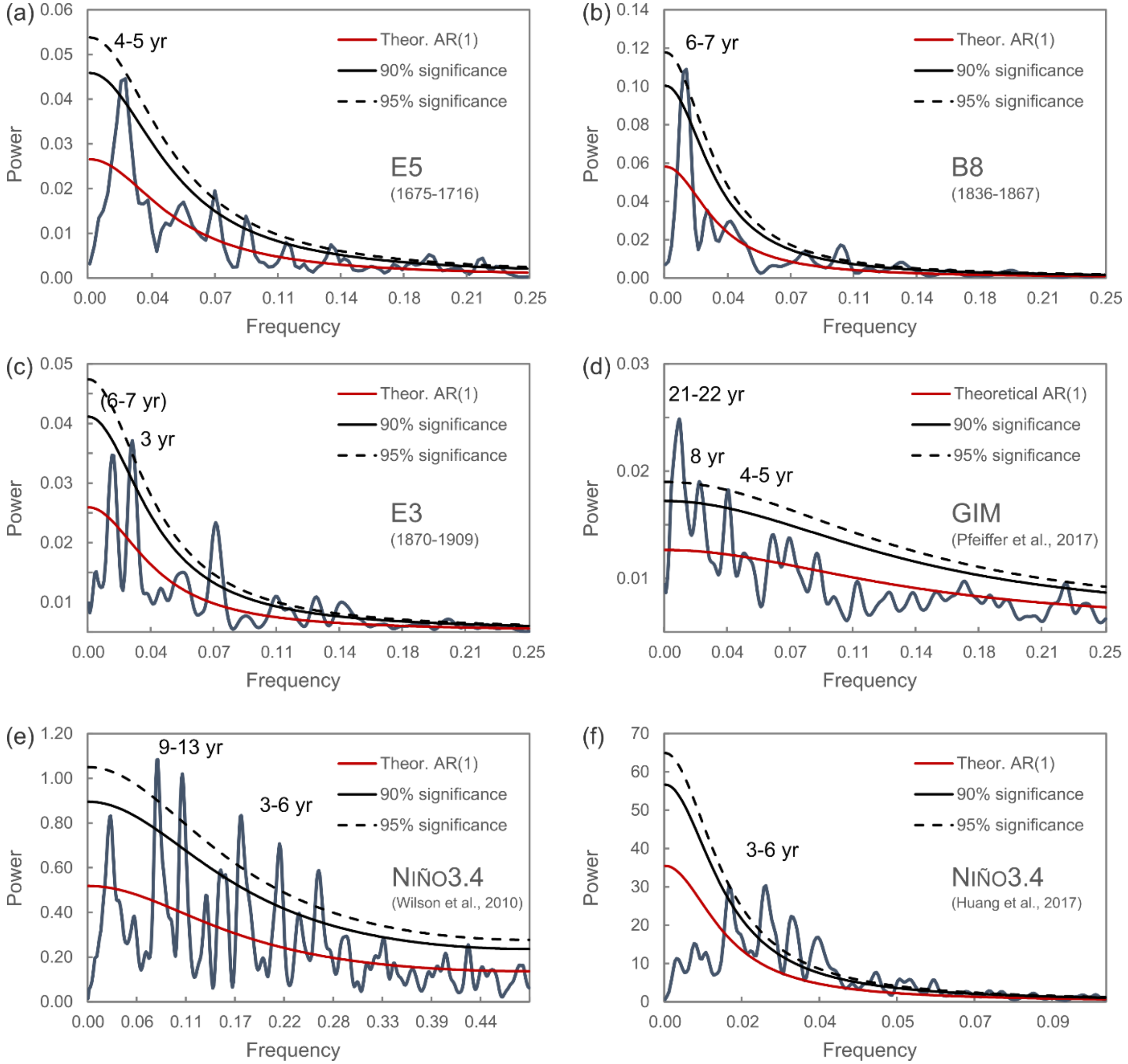

Figure S11: Power spectrum analysis plots for detrended coral SST, the annually resolved Wilson Niño index (Wilson et al., 2010) and the monthly resolved Niño3.4 index based on NOAA ERSSTv5 (Huang et al., 2017) time series.

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9 Linear regression

Ordinary least square (OLS) regression and *PearsonT3* calculation results reveal no significant linear relation between annual coral SST records and the Wilson Niño index (Table S2).

Method	Coefficient	E5 (1675-1716)	B8 (1836-1867)	E3 (1870-1909)	GIM (1880-1995)
Excel OLS	R^2 (p-value)	4.09E-5 (0.9679)	0.0006 (0.8979)	0.0027 (0.7502)	0.0444 (0.0232)
PearsonT3	r [95% confidence interval]	-0.006 [-0.361; 0.350]	-0.024 [-0.739; 0.716]	0.052 [-0.418; 0.500]	0.211 [-0.005; 0.408]

Table S2: Correlation coefficients of given coral records with the Wilson Niño index.

Supplementary References

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