Revision article bg-2018-441 for Biogeosciences

We like to thank both reviewers for their constructive and very supportive comments. We have uploaded a pdf providing our answers to the reviewers comments. Reviewer questions are indicated in italics and our answer below.

Reviewer 1:

1) My only wish is that this study would have also included another newly suggested proxy coral Sr-U for SST proposed by De Carlo et al., 2016, which could be performed simultaneously with their ICP-MS analysis, to assess this other suggested proxy along with the others. The method section (line 190) mentions the precision of U/Ca analysis so it seems U/Ca was measured. Why not add Sr-U to the proxy suite that was assessed?

We have tested Sr-U and found that it did not provide reliable SST reconstructions. Furthermore, our aim was to reconstruct bimonthly SST which is currently not possible with Sr-U as it requires averaging multiple data points to estimate temperature for one value and therefore makes it impossible to do direct comparisons of the methods. We have therefore not included such an assessment in the present paper and do not show U/Ca since it does not add to the interpretation. We add some figures here to show the results which we feel do not warrant inclusion, but the coral community might find it helpful since our comments will be published with the paper. Here, our focus is on testing Li/Mg vs. Sr/Ca and their combination for bimonthly time series.

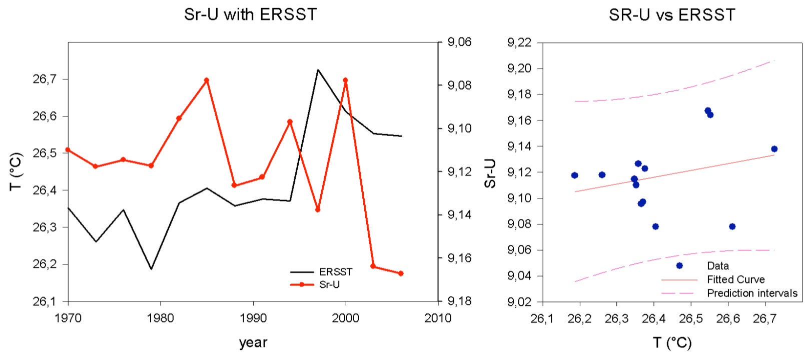


Figure - Left) 3 years averages of EU3 Sr-U (red) compared with NOAA ERSST4 (black). Right) Weighted regression of 3-year averaged Sr-U with ERSST (not significant). Sr-U was calculated following the method in De Carlo et al. (2016). No correlation was found between Sr-U and SST.

2) Move the paragraph in section 3.3 Coral growth parameters and SST to the first section in the Results.

Done.

3) In the methods section (lines 167–170) clarify if Coral XDS was performed on a single *transect or replicate transects. Were these CoralXDS transects the same as your micro-sampling for geochemical analysis?*

Transects for CORALXDS were not the same. For geochemistry we have adopted a much more stringent approach to sample the main growth axes. Our age model confirmation with Sr/Ca seasonality was applied to cross-check CORALXDS results, as shown in Supplementary Figures S1 and S2.
We have added the CORALXDS sampling transects to the Supplementary figures S1 and S2 as dashed lines.

4) What were the lowest extension years? Any fall below the Porites threshold of 5 or 6 mm/year? If not, vital effects should not be a problem.

None of the years fall below 5mm/yr extension rates, ranging between 7-18mm/yr. Only one year in EU3 (1983) showed 5mm/yr in the CORALXDS data which was corrected with our Sr/Ca extension rate data. We now have included a Supplementary Table S2 listing all annual growth data since 1968.

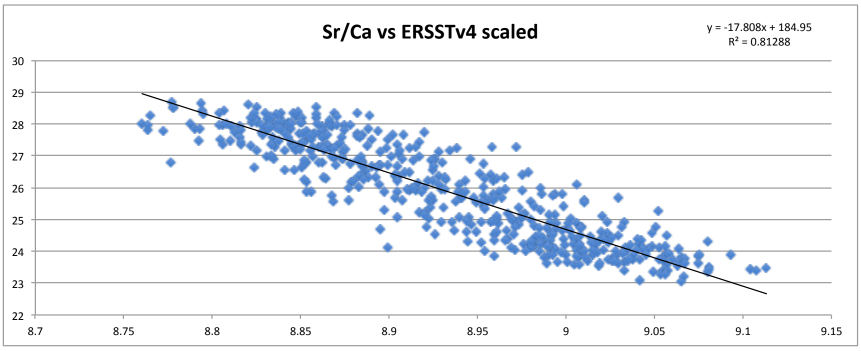
5) Methods Line 190-191 The normalization of Sr/Ca with JCP-1, what about Li/Ca and Li/Mg? What is the precision for Li/Mg and Li/Ca?

All data is referenced to JCp-1, but we also include in coral *in-house* standards for long-term precision of TE/Ca and Li/Mg data. We have adjusted the methods section to align with the former statement and added Sr/Ca, Mg/Ca and Li/Mg values and RSDs in JCp-1 and the in house standard 'Davies Reef'.
It now reads:
"The Sr/Ca, Mg/Ca and Li/Mg data reported here are normalized to the JCp-1 *Porites* sp. standard prepared by the Geological Survey of Japan (Okai et al., 2002) with Sr/Ca = 8.85 mmol/mol (2σ RSD = ±0.41%), Mg/Ca = 4.20 mmol/mol (2σ RSD = ±0.90%) and Li/Mg = 1.47 mmol/mol (2σ RSD = ±1.04%) (N = 17). The Li/Ca data was estimated dividing the Li/Mg by the Mg/Ca data. Long-term reproducibility was determined using the UWA *in-house* Davies Reef coral standard solution with Mg/Ca = ±6.24%, Sr/Ca = ±0.45% and Li/Mg = ±1.39% (2σ RSD; N = 139) (D'Olivo et al., 2018)."

6) Figure 4 and Figure S3 Time assignment. There seem to be three clusters of data in all the plots. This is odd, there should not be clusters of data. Double check your Analyseries time assignment, something is off, see next item.

We checked the linear regressions for monthly vs bimonthly interpolated data with regards to the clusters of data. We found that the clustering increases with decreasing resolution of the SST data, both in terms of spatial (from 0.25° to 2° gridded SST data) and temporal (from monthly to bimonthly) scales. ERSST4 (2°x2° gridded) shows the most extreme clustering, while it is much less for AVHRR OISST. The reason for the clustering is the sudden jumps in

SST between seasons at bimonthly time scales. Our monthly interpolated data don not show clustering (see figure below) confirming our age model. We, however, prefer to work with bimonthly interpolated data since our sampling resolution (6-9 samples per year) is better suited for it.
We have now used 2 anchor points (summer and winter) for our age assignment which did not change the regressions or any conclusions drawn from our work. The methods section has been amended accordingly. Corals never grow constantly between summer and winter in subtropical sites like Europa, the SST seasonality varies between 4.5 and 6°C, so significant SST contrasts between seasons do prevail probably affecting density banding.



7) Looking at the residuals plot (Figures 5 and 6) and the methods lines 197–200, I see there is a sinusoidal character in the residuals.

The sinusoidal character of the residuals is most apparent between the 1980-1992 period (Figure 5d). For this particular period, the amplitudes in our TE/Ca SST reconstructions do not match those in instrumental AVHRR-OISST. The latter indicates very low seasonality in several years between 1980 and 1992, far lower than post-1992. It is beyond our capacity to check the quality of AVHRR-OISST in the oldest part of their record. We believe that the mismatch does not relate to the number of anchor points chosen (we have chosen 2 as requested by the reviewer) for calibration. The differences between coral-derived SST and instrumental record reflect either real differences in local SST or a combination of unknown vital effects and temperature.
Figure 6 indicates SST anomalies (seasonality removed) and their residuals (difference between instrumental SST anomaly and coral-derived SST anomaly).

8) I do not see any major issues with your linear regression plots (Figure 4) but if you reverse the regressors, you get a different solution. OLS will either over fit or under fit the proxy data to SST, depending which regressor is the independent regressor. Reduced Major Axis regression is better and takes error in both regressors into account. Weighted least squares regression is even better (York and Evensen, 2004; Thirumalai et al., 2011) since you can vary the error for each data point. However, this switch in regression method should not change your slopes greatly but should reduce your RSME results. The bigger issue is the serial correlation. WLS can take this serial correlation into account in the regression and it increases your confidence intervals, but it would be better to just remove it.

Our regression analysis was done in Matlab using the Weighted Least Squares Regression, which we named 'robust regressions' in the figure captions. We apologize for having missed to report this, and have now included it in the methods section. All absolute SST reconstructions are based on WLS regression, including the results for the residuals. Autocorrelation is accounted for in our WLS regressions.

We normally use OLS, and not RMA, because it is the method of choice for coral Sr/Ca-SST regressions (Solow & Huppert, 2004). This is because the relationship of coral Sr/Ca and SST is clearly asymmetric (SST determines coral Sr/Ca, it cannot be the other way round). This is the major criterion for the use of OLS, not the question whether there are errors in the SST observations or not (see e.g. Smith, 2009 "Use and Misuse of the RMA for Line-Fitting" for a discussion). (RMA should be used for symmetric relationships.)

The biggest problems with the application of RMA for coral-Sr/Ca calibrations are the unknown errors. This is nicely summarized in Solow and Huppert (2004). RMA assumes that the error variance in the SST observations equals the error variance of the Sr/Ca determinations. There is no reason to believe that this assumption is warranted. The RMA method can be extended to allow for differences in the error variances (see refs in Solow and Huppert, 2004). To do so, it is necessary to have an estimate of both the SST and Sr/Ca error variance. However, it is practically impossible to determine the error variance of coral Sr/Ca determinations, as these include not only the analytical error but also other factors such as vital effects or skeletal heterogeneities.

However, in our study we opted for weighted least squares regression in line with the suggestion of reviewer 1.

Sr/Ca and Li/Mg were used in age assignments since they are the most robust SST proxies to date. We have not opted for assigning the age model with other TE/Ca ratios. We agree with the reviewer that RMSE will therefore always be better for Sr/Ca and Li/Mg then other TE/Ca ratios.

9) Line 192 After doing your own very nice and comprehensive calibration study, why use Correge's –0.0607? Your slopes are lower than his and in my assessment, a better calibration study than Correge's that was just the average for all published studies to date (2006), regardless of the calibration method, SST data used, the possibility of using sub-optimally sampled corals for calibration, etc. Things have vastly improved from 2006 and I would not trust a community average value anymore. See recent paper by (Murty et al., 2018).

We have chosen the Correge slope of -0.061 mmol/molºC^{-1} for the SST anomaly conversion only because this slope is better suited to look at interannual SST changes at regional space scales (not local) following Gagan et al., 2012. Gagan even suggested to use -0.084 mmol/molºC^{-1}. To our opinion, the -0.061 slope is best suited for SST anomaly conversions as shown in previous work (Pfeiffer et al., 2017). However, all absolute bimonthly SST reconstructions are based on our local regression slopes.

10) Line 464–468, Figure 2 and Methods. It is not mentioned if you cleaned the corals to remove any endolithic algae, tissue layer or biological residue. Corals for Mg analysis are *generally cleaned with bleach since Mg is present in biological tissues. In Figure 2, the Mg/Ca is high in the tissue layer, this section should be excluded from the Li/Mg and Mg/Ca data and analysis. Is there any dirty or algae present in the coral skeletons that could be influencing the Mg?*

We have already reported the cleaning method in the methods section of the original paper in lines 165-166. We have cleaned the corals following the protocol of Nagtegaal et al. (2012). We have excluded the top-most samples from the interpretation since certain TE/Ca ratios still showed an effect despite rigorous cleaning. The latter could well be an effect of the lower densities in the top mm where precipitation efficiency differs from underlying material.

11) For your regression analysis, why not combined the two corals to see if the results improve?

Corals EU2 and EU3 have offsets in their mean values, so its not easy to combine them. We have, however, combined proxies when assessing proxy and SST anomalies. Here, we found rather excellent agreement between cores and with SST anomalies.

12) Table 2 How were degrees of freedom determined? Was if adjusted for serial correlation? For EU3 it seems the Sr/Ca and Li/Mg are repeated in rows 9–12 or is this the average of EU2 and EU3 with the label missing in column 1?

The regressions applied assume a DOF = N-2, as indicated we used WLS as suggested by the reviewer.

Rows 9 and 11 show the regression parameters for the longer period 1981-2012 for EU3 Sr/Ca and Li/Mg, respectively, with AVHRR-OISSTv2. Rows 10 and 12 show the regression parameters for the period 1970-2012 for EU3 Sr/Ca and Li/Mg, respectively, in relation to ERSST4. This is indicated in the figure caption and periods in last column of Table 2.

13) Table 3 What is the second row for EU3 for? Is this EU2 and EU3 averaged together? Table 3 Why are you reporting a standard deviation for RSME? RSME does not have a standard deviation, it is a version of deviation itself between the calculated and measured. RSME is reported as since you take the square root of the sum of the deviations divided by the number of pairs.

The second row for EU3 in Table 3 is for the RMSE for the longer period 1981-2012.
We have omitted the standard deviations, thanks for pointing this out. These numbers indicated the spread in RMSE for individual years over the period considered.

14) Table 4 and all correlations. Give the degrees of freedom (adjusted for serial correlation), # of pairs, and p-values for all correlations.

The number of pairs (period in years) and p-values (stars) are indicated in the legend of Table 4. DoF are now added.

15) Figure 2 Can you add the raw trace elemental ratios to the supplemental figures so time assignment can be verified?

Done. New Figure S4 added.

16) Line 59 Add a reference for trade route statement. I believe the southeastern coast of Africa was part of trade routes before the mid-19th century. ICOADs (V3.1) now goes back to the 1600s (Freeman et al 2017, doi:10.1002/joc.4775) but ERSST stops at 1854. Additionally, there is a newer version of ERSST (V5) that includes new ICOADS data (Huang et. al, 2017 doi: 10.1175/JCLI-D-16-0836.1). Does this version give you any better data coverage for your study site and improve the assessment?

ERSST5 does not provide improvements to ERSST4. In fact, at the coarse resolution of ERSST data (2°x2° gridded) no differences exist between the latest versions of ERSSTv3b, ERSST4 or ERSST5 at the coral reef scale. We have therefore opted for ERSST4 which has been tested more widely in several climatology papers.

17) Lines 87–94 There is another coral Li/Mg study (Fowell et al., 2016) that looked at intra-reef variability with a different coral species from the Atlantic and combine Sr/Ca and Li/Mg. That study should be included here but examine the coral sampling in their figure carefully, there were some sub-optimal sampling issues with their corals. The study Montagna et al., 2014 did look at several species of corals, but not the one used by Fowler 2016, so it worth including the Atlantic study in your discussion of previous Li/Mg studies.

Done. We added to discussion:"Applying the -0.097 mmol/mol per °C for Caribbean *Siderastra sidera* forereef corals would underestimate SST anomalies (Fowell et al., 2016)."

18) Line 154-156 Please give the interval for the air temperature records

Done.

19) Line 161 Please clarify, is the depth of 12 and 13 m the water depth of the top of the coral colony where the cores were removed, or the water depth of the base of the coral? Did you sample the whole colony? Just trying to see how big these colonies were. Table 1 Add units for Length

The depth of 12 and 13 m corresponds to the water depth at the base of the megacolonies. Approximately less than half of the colony EU3 was sampled as we estimate its height to ~3.50 m and its width to 6m. The core top is therefore at 8.5-9.5 m.

Reviewer 2:

1) *In my opinion, it is circular to reconstruct SST from trace element-to-Ca data of the same time interval and specimens that were used for proxy calibration. The calibration (+ verification) and reconstruction intervals must be separate, or at least this approach would require different colonies (of both species) for calibration/verification and reconstruction,*

respectively. One possibility is to limit the calibration interval to 2003-2012 and apply the resulting model then just to the pre-2003 section of core EU3. You could also limit the reconstruction interval to 1970-1980 of EU3, because this time interval was – according to Figure 4 – not used for calibration; both options would still miss a verification interval though. Another possibility is to just present regression models spanning the entire lengths of the cores. Alternatively, the authors use the calibration model by D'Olivio et al. (2018) to estimate SST and compare those data to instrumental SST.

The calibration periods were all indicated in the figure captions. We have now also included it in methods. We have opted for using the regression model that spans the period of overlap with satellite SST between 1981-2012 for the long core EU3 and 2003-2012 for the short core EU2. Table 2 shows the regressions for different calibration periods. However, our main aim is not the quantification of absolute SST, rather relative changes in SST (anomalies) and how they compare to SST records. We have added a paragraph to the discussion in which we assess the multiproxy method from D'Olivo et al. (2018) applied to our corals.

2) *I am missing details on how exactly the Sr/Ca and Li/Mg data were combined. Is the composite Sr/Ca-Li/Mg SST proxy based on a multi-regression model? The equation for this regression model should be provided.*

We calculated the arithmetic mean between Sr/Ca-SST and Li/Mg-SST.

3) *There is some inconsistency regarding the statement on proxy reliability of Sr/Ca and combined Sr/Ca-Li/Mg (compare, e.g., L461-463a and L508/9). Authors should say more clearly (in the main text and in the Abstract) that relative SST changes are reflected equally well by both proxies, but Sr/Ca is still superior to quantify SST. The current Abstract is too vague as the main findings are concerned. It also remained unclear how a combination of Sr/Ca and Li/Mg can "improve SST reconstructions". Table 3 does not support this claim, because RMSE errors are, on average, lower for Sr/Ca-based SST estimates than for those computed from combined Sr/Ca-Li/Mg.*

We have modified the abstract. It now reads: "In our study, Sr/Ca is still superior to Li/Mg to quantify absolute SST and relative changes in SST."
Regarding the combined Sr/Ca-Li/Mg-SST, Table 3 does show improvement relative to Sr/Ca or Li/Mg only for shorter core record EU2. RMSEs are lower for the combined proxy. The latter hints at the possibility that combined Sr/Ca-Li/Mg can improve SST reconstructions when both proxies work equally well.

We have modified the section in lines 508 onwards and it now reads:
"Overall the results from this study indicated that Sr/Ca is still superior to Li/Mg and was the most reliable SST proxy when applied to a longer time series. However, the excellent agreement between Sr/Ca and Li/Mg and their combination in core EU2 demonstrated that both SST proxies and their combination can provide with greater confidence, more reliable SST reconstructions with lower RMSEs (D'Olivo et al., 2018)."

4) *The authors need to better describe the innovative aspect of the study. In particular, they need to highlight (in the Introduction) how their work differs from D'Olivio et al. (2018) and Montagna et al. (2014) (e.g., how much longer were the new coral records in comparison to previous studies; which species were used here and in previous works; how compare the results?).*

In the Introduction we stated that our record is the first application of the Li/Mg proxy on a multi-decadal scale for *Porites* corals.

5) *Linear regression equations may have been the most obvious to use in a mathematical sense, but the actual relationships between trace element-to-Ca ratios (or TE/TE) and SST are nonlinear (compare Gaetani & Cohen 2006; Montagna et al. 2014 etc.). Would it not be better to work with non-linear equations?*

All regression models for the proxies used in this paper are linear models, which hold for the narrow SST range at our coral site (22-29 °C). This is in line with all tropical corals shown in Montagna et al. 2014 and D'Olivo et al. 2018, which fall on a linear regression line. The exponential relationship for Li/Mg vs SST applies to the entire suite of carbonate secreting archives that grow at vastly different SST.

6) I may be worth mentioning somewhere in the Discussion that the Li/Mg serves a more robust thermometer at low temperatures because of the non-linearity of Li/Mg vs. SST relationship.

Done.

Other issues: L22: It should read "temperature proxy"
Done.

L25-26: Coral = archive, Sr/Ca etc. = proxy. Rephrase sentence accordingly.
Done.

L51-53: It should read "The oceans respond". If two full sentences are linked by conjunction, a comma must precede "and".
Done.

L54: replace semicolon by comma
Done.

L55-58: This sentence needs to be rephrased. Three times "climate" in one sentence. Complicated phrasing.
Word 'climate' removed in one instance

L76-78: Here you list the slope ranges, but not provide the values revealing the different strengths of the correlations.
The strength of correlations is not assessed here; it is merely a listing of slopes from the literature.

L81: "bio-smoothing effects": Explain. Has this expression been used in cited papers?
This expression has been used by Gagan et al. (2012) and is cited.

L201: Tell the reader how long were the calibration intervals in EU3 and EU2.
Calibration periods don't apply here. They are reported in section 3.3 where it is required.

L226: I would not call 9 years “long-term”.
It refers to the longer period used for anomalies, it reads “Longer time series anomalies were calculated relative to the 1981 to 2010 period.”

L228/9: "record’s lowest ratios" or just "lowest ratios"
Not changed.

L232: I do not understand what you mean: "showed higher values between 2003 and 2012"? Offset relative to what? Why "absolute"?
added “relative to EU3..”

L233: “Li/Mg between EU2 and EU3: : :”: Replace “between” by ”of”
Done.

L237: “EU3 showed larger amplitude seasonal variations”: Delete “amplitude”
Done.

L262/3: “The Sr/Ca and Li/Mg time series of cores EU3 and EU2 were highly consistent in the period of overlap: : :”. What does “consistent” mean here? Rephrase.
We deleted this sentence.

L264 (and other occasions in ms): “Li/Mg performed equally well”. Odd phrasing; unclear what you mean exactly.
We deleted this sentence.

L285: “AVHRR-OISST2 display a more limited seasonality: : :”: Delete one “S” in “OISST”; replace “more limited” by “truncated” or “attenuated”.
Done.

L291: “reference period” should read “reference periods”
Done.

L295: Following Table 2, Sr/Ca-SST slopes are lower than the average reported in Corrège (2006); so this sentence needs to be rephrased.
Latter part of sentence was removed.

L321: replace “cooler temperature anomalies” by “smaller anomalies”
We replaced it with ‘colder anomalies’ because that is what we are trying to convey here.

Table 2 and elsewhere: Use consistent number of decimals throughout ms (including Figures and Tables), i.e., instead of a slope of "-0.04", write "-0.040".

We adjusted all slope and p-values to three numbers of decimals.

Figure 2: Comparison would be facilitated if scaling of the y-axes was the same.
We deliberately did not scale the y-axes the same because absolute proxy values have an

offset. Plotting all on the same y-axes would make the seasonality harder to spot. We therefore did not re-scale y-axes in Figures 2 and 4. Figure 3 illustrates all proxy versus proxy relationships on the same axes for both cores, complementing Figure 2.

Figure 4: ditto for x and y-axes. Also check all other figures.
We deliberately did not scale the y-axes the same because absolute proxy values have an offset. Here, we show the regression plots for both cores reflecting their individual relationship with SST. We therefore did not re-scale this Figure 4.

kind regards,
Zinke and co-authors

Multi-trace element sea surface temperature coral reconstruction for the southern Mozambique Channel reveals teleconnections with the tropical Atlantic

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Abstract

Here we report seasonally resolved sea surface temperatures for the southern Mozambique Channel in the SW Indian Ocean based on multi-trace element temperature proxy records preserved in two *Porites* sp. coral cores. Particularly, we assess the suitability of both separate and combined Sr/Ca and Li/Mg proxies for improved multi-element SST reconstructions. Overall geochemical records from Europa Island *Porites* sp. highlight the potential of Sr/Ca and Li/Mg ratios as high-resolution climate proxies but also show significant differences in their response at this Indian Ocean subtropical reef site. Our reconstruction from 1970 to 2013 using the Sr/Ca-SST proxy reveals a warming trend of 0.58 ± 0.1 °C in close agreement with instrumental data (0.47 ± 0.07 °C) over the last 42 years (1970 to 2013). In contrast the Li/Mg showed unrealistically large warming trends, most probably caused by uncertainties around different uptake mechanisms of trace elements Li and Mg and uncertainties in their temperature calibration. In our study, Sr/Ca is superior to Li/Mg to quantify absolute SST and relative changes in SST. However, spatial correlations between the combined detrended Sr/Ca and Li/Mg proxies compared to instrumental SST at Europa revealed robust correlations with local climate variability in the Mozambique

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Channel and teleconnections to regions in the Indian Ocean and southeastern Pacific where surface wind variability appeared to dominate the underlying pattern of SST variability. The strongest correlation was found between our Europa SST reconstruction and instrumental SST records from the northern tropical Atlantic. Only a weak correlation was found with ENSO, with recent warm anomalies in the geochemical proxies coinciding with strong El Niño or La Niña. We identified the Pacific/North American (PNA) atmospheric pattern, which develops in the Pacific in response to ENSO, and the tropical North Atlantic SST as the most likely causes of the observed teleconnections with the Mozambique Channel SST at Europa.

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1 Introduction

Ocean-atmosphere dynamics in the tropics are key drivers of large-scale climate phenomena, such as the El Niño-Southern Oscillation (ENSO) (Angell, 1990; Trenberth et al., 1998; Xie et al., 2010; Timmermann et al., 2018). Tropical climate variability has therefore a strong impact on regional and global climate teleconnections. These ocean-atmosphere dynamics are temporally variable and sensitive to small perturbations in sea surface temperature (SST) associated with natural and anthropogenic climate change. The oceans respond to the combined effects of natural variability, and greenhouse driven anthropogenic warming act at seasonal, interannual and multi-decadal scales. The complexity of the climate system at temporal and spatial scales, therefore, call for a comprehensive assessment of SST pattern change in historical times (Xie et al., 2010). To investigate changing tropical climate and model potential future scenarios, the modern climatology faces the challenge of improving data coverage, especially extending the limited time length of instrumental measurements. The earliest records of SST, measured by commercial ship traffic, mainly along trading routes, started in the mid-19th century (Freeman et al., 2017). Only with the arrival of satellite technology in the 1980's have the oceans been covered in more detail. The limited number of observations and drop in data quality prior to the 1980's cause considerable uncertainties in our understanding of important climate interactions (Thompson et al., 2008; Pfeiffer et al., 2017). These limitations make the use of paleoclimate reconstructions, particularly from remote locations, a vital tool to learn about past climate conditions.

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Coral reconstructions extending back decades to several centuries provide invaluable data to assess past tropical climate variability (Hennekam et al., 2018; Pfeiffer et al., 2017). One of the most robust and widely used geochemical proxies to reconstruct SST in tropical areas is the Sr/Ca ratio from massive corals like *Porites* (Corrège, 2006; Pfeiffer et al., 2009; DeLong et al., 2012). The Sr/Ca ratios in $CaCO_3$ precipitated during skeletal formation are negatively correlated with temperatures, i.e. as temperatures increase, less Sr is incorporated into the aragonite lattice relative to Ca (Alibert and McCulloch, 1997; Corrège, 2006; DeLong et al., 2007). While the Sr/Ca proxy is a remarkably useful tool for paleoclimate reconstructions, there are a number of limitations that need to be considered in the application of this proxy for quantitative reconstructions. Among these, there is a significant difference in the Sr/Ca temperature dependency of biogenic and experimentally precipitated inorganic aragonite (Smith et al., 1979). Abiogenic aragonite has a significantly stronger Sr/Ca dependence to temperature with a slope of -0.039 to -0.044 mmol/mol°C^{-1} than the coral skeletal Sr/Ca with slopes ranging between -0.040 to -0.084 mmol/mol°C^{-1} (Smith et al., 1979; Cohen et al., 2002; Gaetani & Cohen, 2006; Gaetani et al., 2011; De Carlo et al., 2015). This disparity has been considered as the influence of strong "vital effects" during the coral biomineralization process (de Villiers et al., 1995) or bio-smoothing effects (Gagan et al., 2012). Nevertheless, several recent studies have confirmed the suitability of the Sr/Ca paleorecorder when carefully sampled along the optimal growth axis and ideally replicated (Pfeiffer et al., 2009, 2017; De Long et al., 2012; Zinke et al., 2016). Recently, the use of additional SST sensitive proxies (multi-element paleothermometry) has been tested and the Li/Mg ratios emerged as a promising tool to reconstruct SST (Hathorne et al., 2013; Montagna et al., 2014; Fowell et al., 2016; D'Olivo et al., 2018). The innovation of the Li/Mg temperature proxy lies in the normalization of Li to Mg, which is thought to eliminate the influence of Raleigh fractionation processes influencing most trace element incorporations into the coral skeleton (Cohen et al., 2002; Gaetani & Cohen, 2006; Gaetani et al., 2011). Li/Mg was shown (e.g. Montagna et al., 2014) to be applicable to a large range of coral species inhabiting a large temperature range. However, to date no long-term (e.g. multi-decadal) SST reconstruction has been developed based on Li/Mg ratios to test its suitability, particularly in tropical corals, in comparison to the established Sr/Ca time series.

The aim of this study was to reconstruct sea surface temperatures based on coral Sr/Ca, Li/Mg and their combination to validate and extend the SST information for the southern Mozambique Channel in the southwestern Indian Ocean. We examined instrumental climate and coral proxy data from Europa Island. The high latitude of this atoll and the lack of human impact make this location ideal to investigate past climate variability based on cores from

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massive *Porites* corals (Fig. 1). The Mozambique Channel in the southwestern Indian Ocean is a particular sparsely sampled region, despite its importance as a major pathway of warm surface flow of the global ocean conveyer (De Ruijter et al., 2002; Schouten et al., 2002; Woodruff et al., 2011; Beal et al., 2011). Furthermore, Europa Island is located just upstream of the region that feeds the Agulhas Current, one of the most powerful western boundary currents on the planet. As such, this region is a possible source of both local and global climate interactions and drivers of especially longer-term changes in patterns of SST variability, which are investigated here.

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2 Materials and Methods

2.1 Study area

Europa Island (hereafter Europa), a 28 km^2 atoll that is part of the five *Eparses* Islands, of the French *Terres Australes et Antarctiques Françaises*, and lies in the central Mozambique Channel between southern Mozambique and southern Madagascar (22° 21' S, 40° 21' E; Fig. 1). Europa, with Hall Tablemount and Bassas da India Atoll, is part of an archipelago that was hypothesized to have been formed by the Quathlamba hotspot, which presently lies beneath Lesotho (Hartnady, 1985). Europa is a carbonate platform attaining a maximum elevation of 6 m with a fossil coral terrace that was dated to the last interglacial period with an age of approximately 94 kyr (Battistini et al., 1976), therefore formed concomitantly to other carbonate platforms in the Mozambique Channel (Battistini et al., 1976; Guillaume et al., 2013). The 22 km coastline is surrounded by a fringing coral reef with a fore reef slope that dips steeply into deeper water. A geomorphological relict of the former atoll drained by the following marine regression forms a narrow shallow lagoon that occupies more than the half of the island and opens to the sea through the northern reef flat. A mangrove formation ranging from shrub to forest stands grows in the salt waters of the back and windward edge of the lagoon (Lambs et al., 2016). Europa is characterized by a high-energy environment under the influence of south to southeasterly trade winds (strongest in austral winter) and occasionally impacted by tropical cyclones in austral summer (Barruol et al., 2016). A train of anticyclonic ocean eddies traveling through the Mozambique Channel transports tropical water southward eventually feeding the Agulhas Current (Beal et al., 2011).

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Europa is a no-take area; the pristine state of its fringing coral reefs was attested by scarce macroalgae, high fish biomass and high coral coverage that locally exceeded 80% due to superimposed platy *Acropora* stands (Guillaume & Bruggemann, 2011). While almost

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undisturbed from local anthropogenic disturbance, remote islands are impacted by global change. For instance, in 1998 (El Niño) a severe coral bleaching event was inferred at Europa from a high coral mortality accompanied by a recruit cohort of small-sized *Acropora* colonies observed 4 years later (Quod & Garnier, 2004). In 2011 (La Niña), a moderate bleaching event affecting mostly *Pocillopora* corals, massive and branching *Porites* was witnessed (Guillaume & Bruggemann, 2011).

2.2 Instrumental temperature data

To review and evaluate the coral geochemical proxies, various sources of instrumental data were assessed. High-resolution SST data (0.25° × 0.25°) covering 1981 to 2013 was obtained from the Advanced Very High Resolution Reconstructed Optimum Interpolation Sea Surface Temperature version 2 (AVHRR-OISSTv2; Banzon et al., 2014, 2016; Reynolds et al., 2007). The AVHRR-OISSTv2 dataset is composed of daily satellite data and in *situ* data, adjusted for biases (Banzon et al., 2014). The SST data was extended back to 1970 using the Extended Reconstructed Sea Surface Temperature (ERSSTv4; Liu et al., 2015) dataset, which is based on the "International Comprehensive Ocean-Atmosphere Data Set" (ICOADS; Woodruff et al., 2011). The ESRSSTv4 record is composed of satellite data from the AVHRR data extended with temperature records from ships and buoys processed at monthly resolution and interpolated to a spatial resolution of 2.0 degrees. In addition, *in situ* SST data was available from April 2009 to October 2010 measured by a tide-temperature-conductivity XR-420 6.30 RBR Ltd gauge deployed by the CNRS-INSU close to the *Porites* coral coring site studied here (Testut et al., 2016). Finally, *in situ* air temperature records were provided by the Meteo-France station at Europa between 1970 and 2013 (n° 98403003, 22.32 °S, 40.33 °E, elevation 6 m).

2.3 Coral core sampling, analysis and age model

Coral cores were extracted with a pneumatic drill in sections of ~30 cm from two living massive *Porites* colonies on the northeastern reef slope of Europa in early May 2013 during the *ORCIE* scientific expedition. The cores were obtained at a depth of 12 m to 13 m at the base of the colony with the core top at 8.5-9.5 m depth. Morphological identification based on skeletal features observed under an optical microscope assigned core EU2 to *P. solida* and core EU3 to *P. mayeri*. The longest core EU3 measured 136 cm (Table 1) and was sampled from 2013 back to 1970. The shorter core EU2 was sampled from 2013 back to 2003. Cores

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were sliced to 7 mm thick slabs and cleaned following established protocols (Nagtegaal et al., 2012). The slabs were then X-rayed to reveal the annual density banding and analysed by densitometry along single transects at the Australian Institute of Marine Science (Figs. S1 and S2). Annual rates of linear extension were calculated from 1) X-ray based density measurements with CoralXDS software (Helme et al., 2002) and 2) the bimonthly Sr/Ca records by measuring the distance between Sr/Ca maxima in both records.

The basis for the optimal extraction of geochemical signals from massive *Porites* is the precise selection of the sampling path, according to the architecture of the coral skeleton. The X-rays show the corallite fan structures with the chosen sampling path along the central growth axis of the corallum highlighted (Figs. S1 and S2). Carbonate powder samples of approximately 50 mg at 2 mm continuous intervals were obtained along this sampling path with a 0.9 mm diameter dental drill. Processing of the samples for geochemical analysis is based on methods described by Zinke et al. (2015) and D'Olivo et al. (2018). First the powder samples were homogenized in a small agate mortar and ~10 mg were weighed into thoroughly cleaned 5-ml tubes. Subsequently the samples were dissolved in 0.5 ml of 0.5 N HNO3 and diluted to a calcium concentration of 100 ppm by taking an aliquot of 38 ml from the primary dissolution and adding 3 ml of 2 % HNO_3 and used for the analysis of Li and Mg. A second aliquot for the analysis of Sr, Ca, and Mg was prepared at 10 ppm by using a 300 ml aliquot of the first dilution and adding 2.7 ml of 2 % HNO_3 spiked with trace concentrations of scandium, praseodymium and yttrium used as internal standards. The analyses for trace element concentrations (TE) were made on a Thermo Scientific XSERIES 2 quadrupole ICP-MS (inductively coupled plasma mass spectrometer) at the University of Western Australia (UWA). The Sr/Ca, Mg/Ca and Li/Mg data reported here are normalized to the JCp-1 *Porites* sp. standard prepared by the Geological Survey of Japan (Okai et al., 2002) with Sr/Ca = 8.85 mmol/mol (2σ RSD = ±0.41%), Mg/Ca = 4.20 mmol/mol (2σ RSD = ±0.90%) and Li/Mg = 1.47 mmol/mol (2σ RSD = ±1.04%) (N = 17). The Li/Ca data was estimated dividing the Li/Mg by the Mg/Ca data. Long-term reproducibility was determined using the UWA *in-house* Davies Reef coral standard solution with Mg/Ca = ±6.24%, Sr/Ca = ±0.45% and Li/Mg = ±1.39% (2σ RSD; N = 139) (D'Olivo et al., 2018).

The first step after generating the trace element records was to assign an age model. The 2 mm sampling resolution provided 6 to 9 samples per year for any given year and provided robust bimonthly resolved geochemical records. Based on the instrumental SST data from

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AVHRR-OISSTv2 and the *in situ* measurements the coldest bimonthly period (on average July/August) and the warmest bimonthly period (on average February/March) for any given year was established for our location. The age model was assigned by simultaneously checking the correlation of Sr/Ca and Li/Mg with the AVHRR-OISSTv2 ensuring the maximum correlation possible was obtained for one proxy without compromising the other proxy. The highest Sr/Ca and Li/Mg annual values in the raw data were tied with the annual minimum and the lowest Sr/Ca and Li/Mg to the annual maximum in the SST records using the open source time series analysis toolkit "Analyseries". Bimonthly (6 samples per year) records were generated by linear interpolation in Analyseries to facilitate comparisons between the different datasets.

Calibrations between trace elements and the SST products, and the relationships between different trace elements were obtained using robust regressions, which accounts for heteroscedasticity errors and the presence of outliers in the data. This method uses iteratively reweighted least squares with a bisquare weighting function. In addition to absolute SST values, SST anomalies (deviations from bimonthly SST seasonality in any given year) were calculated relative to the reference period of 2003 to 2012, which includes the overlap between both cores. Longer time series anomalies were calculated relative to the 1981 to 2010 period. Bimonthly temperature residuals were calculated for absolute SST and SST anomaly reconstructions to highlight periods where Sr/Ca-SST and Li/Mg-SST differ from instrumental SST. To evaluate how different trace element ratios tracked the instrumental temperatures, uncertainties in bimonthly absolute SST and SST anomalies for individual and composite cores were calculated based on the root mean square error (RMSE) defined as:

$$RMSE = \sqrt{\frac{1}{N}\Sigma\left(T_{calc,n} - T_{meas,n}\right)^2},$$

where $T_{calc,n}$ is the n'th term from the coral derived temperature and $T_{meas,n}$ is the n'th measurement in the instrumental record and N is the total number of observations.

3 Results

3.1. Coral growth parameters and SST

Linear extension rates based on the distance between annual density bands and the distance between Sr/Ca maxima in both cores displayed interannual and multi-decadal variability (Fig.

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2a; for anomalies see Fig. S3). Linear extension rates in both cores were above 7 mm/yr in any given year. Linear extension for EU3 was within 0.2 cm between the two methods except during 1972 to 1973 and 1983 to 1985. The exceptionally low extension rates during these intervals obtained in core EU3 by the density method (CoralXDS) were most probably related to uncertainties in assessing the chronology due to poorly defined density contrasts (Fig. S2; Table S2). Therefore, for those years, the clear seasonal pattern in Sr/Ca provided a better chronology control than X-ray densitometry. Extension rates measured with the density method in EU2 and EU3 between 1968 and 2012 showed similar values, with a mean of 1.07 ± 0.19 cm/yr for EU2 and 1.2 ± 0.27 cm/yr for EU3, However, the sclerochronology based on the density measured with X-rays had large uncertainties due to poorly defined annual density cycles in EU2 in the older part of the record (Fig. S1). EU2 and EU3 mean extension rates measured between Sr/Ca maxima between 2003 and 2012 were also similar with 1.23 ± 0.14 cm/yr for EU2 and 1.28 ± 0.13 cm/yr for EU3 (Fig. 2a). Interannual extension rates in EU2 and EU3 showed no significant correlation.

Skeletal density in core EU3 displayed lower variability (±0.1 g/cm^3) than core EU2 (±0.2 g/cm^3) with no correlation between cores and no significant trend (Fig. 2b). Interestingly, core EU2 displayed higher density than EU3 in El Niño years 1977/78, 1982/83, 2002/03 and 2010 (Tab. S2). EU3 and EU2 density variations were in anti-phase with extension rates for most of the record. Variability and trends in calcification in both cores were mainly explained by changes in extension rates (Fig. 2c; Tab. S2).

We find no correlation between SST reconstructions or instrumental SST with either extension or calcification rates nor skeletal density in both cores (Fig. 2d). The period of fastest extension and highest calcification in EU3 corresponded to 1947 to 1961 (Tab. S2). No significant changes in extension or calcification rates were associated with known El Niño events (e.g. 1941/42 and 1998) or local cold/warm events recorded by instrumental and proxy records (e.g. 1994, 2002).

3.2 Bimonthly Sr/Ca, Li/Mg, Mg/Ca and Li/Ca ratios

The bimonthly time series of all trace element ratios measured in cores EU2 and EU3 are illustrated in Figure 3. Comparisons between the different trace element ratios for the full

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length of individual records (EU2: 2003 and 2012; EU3:1970-2012) are shown in Figure 4, Figure S4 and Table S1.

For the period of overlap the bimonthly time series of the Sr/Ca ratios of core EU3 ranged between 8.78 and 9.03 mmol/mol (8.77 and 9.09 mmol/mol between 1970 and 2012) and in EU2 between 8.90 and 9.18 mmol/mol (Fig. 3a; Fig. 4a). The mean Sr/Ca ratios of the EU2 core were ~0.1 mmol/mol higher compared to EU3, while seasonal amplitudes and trend since 2003 were similar between cores (Fig. 3a). Sr/Ca ratios for EU2 and EU3 were highly correlated ($r^2 = 0.85$, $p < 0.001$, N = 54). Both cores showed a long-term decrease (warming trend) in Sr/Ca between 2003 and 2012. The time series of EU3 Sr/Ca between 1970 and 2012 showed a non-linear decrease starting in the mid to late-1990s with the records lowest ratios between 1998 and 2000 and 2009 to 2011.

The seasonal range in Li/Mg ratios in core EU3 varied between 1.18 and 1.52 mmol/mol (1.18 and 1.65 mmol/mol between 1970 and 2012) while in core EU2 it ranges between 1.35 and 1.6 mmol/mol. EU2 Li/Mg showed an offset to higher absolute Li/Mg ratios between 2003 and 2012 relative to EU3 (Fig. 3b, Fig. 4a). Li/Mg of EU2 and EU3 were highly correlated ($r^2 = 0.69$, $p < 0.001$, N = 54), although lower than Sr/Ca ratios. The time series of EU3 Li/Mg between 1970 and 2012 showed a non-linear decrease starting in the mid to late-1990s. For the period of overlap between 2003 and 2012, both core Li/Mg ratios showed no trend.

Mg/Ca ratios in core EU3 showed larger seasonal variations than core EU2 (Fig. 3c). EU2 Mg/Ca ratios ranged between 4.24 and 4.61 mmol/mol between 2003 and 2012 while EU3 ranged between 4.40 and 5.36 mmol/mol (4.03 and 5.36 mmol/mol between 1970 and 2012; Fig. 3c, Fig. 4b). EU2 showed lower mean Mg/Ca ratios (~0.4 mmol/mol) than EU3 between 2003 and 2012 (Fig. 3b). Mg/Ca ratios in EU2 and EU3 were significantly correlated, yet lower than Sr/Ca or Li/Mg ($r^2 = 0.34$, $p < 0.001$, N = 54). Overall, EU3 Mg/Ca showed an increase since 1970 with a marked switch post-2005. EU2 Mg/Ca had no trend.

Li/Ca ratios in core EU2 ranged between 6.03 and 7.20 µmol/mol while in EU3 it ranged between 6.04 and 6.87 µmol/mol (5.97 to 6.87 µmol/mol between 1970 and 2012; Fig. 3d, Fig. 4c). Li/Ca ratios in EU2 and EU3 were significantly correlated ($r^2 = 0.33$, $p < 0.001$, N = 54), but lower than Sr/Ca or Li/Mg. Li/Ca was positively correlated with Sr/Ca and Li/Mg and negatively with Mg/Ca in both cores for most of the record (Figs. 4c, e, f; Table S1). EU2 Li/Ca largely mirrored variations in Sr/Ca and Li/Mg, while in EU3 Li/Ca showed lower

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correlations (Table S1). EU3 interannual variability in Li/Ca deviated from the patterns observed in the Sr/Ca, Li/Mg and Mg/Ca data in 1970/71, 1976-78, 1989/90 and between 2001 and 2004 (Fig. 3d). In those years lower EU3 Li/Ca ratios were associated with lower Mg/Ca and higher Sr/Ca and Li/Mg ratios, opposite to the expected relationships (Fig. 3d).

3.3 Calibration of TE/Ca and SST reconstruction

Absolute temperature reconstructions were obtained from the regression of the bimonthly Sr/Ca and Li/Mg ratios with the AVHRR-OISSTv2 and ERSSTv4 data (Fig. 5; Table 2; for ERSSTv4 see Fig. S5 and for Mg/Ca and Li/Ca vs. SST see Fig. S6). Both of the coral datasets showed highly significant ($p < 0.001$) correlation coefficients with the temperature products over the period of overlap (2003 to 2012) with $r^2_{EU3\ Sr/Ca} = 0.92$, $r^2_{EU2\ Sr/Ca} = 0.93$, $r^2_{EU3\ Li/Mg} = 0.78$ and $r^2_{EU2\ Li/Mg} = 0.93$ (Table 2). Correlation coefficients of EU3 Sr/Ca and Li/Mg for the longer periods 1981 to 2012 and 1970 to 2012 with AVHRR-OISSTv2 and ERSSTv4, respectively, were also high (Table 2; Fig. S5). The regression slope of TE ratios with the two SST products varied between -0.040 and -0.051 mmol/mol per °C for Sr/Ca and between -0.045 and -0.064 mmol/mol per °C for Li/Mg (Table 2). Overall, the regression slopes were marginally lower for regressions with AVHRR-OISSTv2 compared to ERSSTv4. Weighted least squares regressions with 1.5 years *in situ* SST data between 2009 and 2010 revealed similar regression slopes for Sr/Ca and Li/Mg but with narrower range (-0.042 to -0.047 mmol/mol per °C for Sr/Ca and –0.045 to -0.052 mmol/mol per °C for Li/Mg) and lower correlation coefficients ($r^2_{EU3\ Sr/Ca} = 0.70$, $r^2_{EU2\ Sr/Ca} = 0.76$, $r^2_{EU3\ Li/Mg} = 0.73$ and $r^2_{EU2\ Li/Mg} = 0.81$). All correlations were statistically significant with $p < 0.050$.

The maximal seasonal range over the period 1970 to 2012 of the reconstructed bimonthly Sr/Ca-SST and Li/Mg-SST varied between 22 °C and 30 °C in both cores with a mean seasonal amplitude of 4.33 ± 0.67 °C (Fig. 5; for ERSSTv4 see Fig. S7) in close agreement with *in situ* SST (4.82 ± 0.05 °C for 2009 to 2010) and regional AVHRR-OISSTv2 (4.67 ± 0.7 °C for 1981 to 2013) and ERSSTv4 (4.52 ± 0.44 °C for 1970 to 2012).

Residuals (calculated as the difference between coral-derived SST and AVHRR-OISSTv2 for individual record length) are presented in Fig. 6 and RMSE's in Table 3 (for ERSSTv4 see Fig. S7). The coral Sr/Ca and Li/Mg-SST reconstructions had the lowest residuals between 1993 and 2012 with AVHRR-OISSTv2, with slightly larger residuals prior to 1993 (core

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EU3). AVHRR-OISSTv2 displayed a truncated seasonality between 1989 and 1995 (warmer winters) with on average higher mean SST than coral-derived SST (Fig. 6; Sr/Ca, Li/Mg and their combination). Summer SST (Sr/Ca, Li/Mg and their combination) was in general in better agreement throughout the individual records. Sr/Ca performed best as SST proxy followed by the combined Sr/Ca and Li/Mg-SST (Fig. 6; Table 3).

Sr/Ca, Li/Mg and SST bimonthly anomalies were calculated relative to the 2003 to 2012 (core overlap) and 1981 to 2010 (coral composite) reference periods. Coral-derived SST anomalies were calculated using the literature average proxy-SST relationships of -0.061 mmol/mol°C^{-1} for Sr/Ca (Corrège, 2006) and -0.060 mmol/mol°C^{-1} for Li/Mg (for *Porites* growing within 25 and 30 °C; Hathorne et al., 2013; D'Olivo et al., 2018). Composite coral-derived SST anomalies were then calculated as the arithmetic mean obtained from the two cores. Residuals were calculated as the difference between coral-derived SST anomalies and AVHRR-OISSTv2 anomalies (for ERSSTv4 see Fig. S8).

Figure 7 illustrates the anomalies (1981 to 2010) for the composite proxy SST from the two cores (individual cores shown in Fig. S9) compared to the SST anomalies from AVHRR-OISSTv2 (for ERSSTv4 see Fig. S8). EU2 and EU3 Sr/Ca and Li/Mg anomalies agreed well between records ($r_{Sr/Ca} = 0.46$, $p < 0.001$, $N = 57$; $r_{Li/Mg} = 0.56$, $p < 0.001$, $N = 57$; Fig. S9). The amplitudes of the EU Sr/Ca-SST composite anomalies closely tracked AVHRR-OISSTv2 anomalies with slightly higher residuals prior to 1993 (Fig. 7a). EU Li/Mg-SST composite anomalies displayed similar variability as AVHRR-OISSTv2, yet the agreement was slightly lower than for Sr/Ca-SST anomalies with a shift to lower mean Li/Mg-SST ($r_{Sr/Ca} = 0.37$, $p < 0.001$, $N = 189$; $r_{Li/Mg} = 0.33$, $p<0.001$, $N = 189$; Fig. 7b). The detrended bimonthly records agreed well between composite Sr/Ca-SST and Li/Mg-SST anomalies ($r = 0.73$, $p < 0.001$, $N = 252$) and with AVHRR-OISSTv2 anomalies ($r_{Sr/Ca} = 0.41$, $p < 0.001$, $N = 189$; $r_{Li/Mg} = 0.31$, $p < 0.001$, $N=189$). As with absolute SST, Sr/Ca-SST and Li/Mg-SST composite anomalies showed larger residuals pre-1993 and in general colder anomalies than in AVHRR-OISSTv2 (Fig. 7c; for ERSSTv4 see Fig. S8). The lowest residuals were found for Sr/Ca-SST and Sr/Ca-Li/Mg combined SST anomalies (Fig. 7d). RMSE's between 2003 and 2012 are lowest for Sr/Ca-SST (0.49 ± 0.35 °C) followed by Sr/Ca-Li/Mg (0.76 ± 0.39 °C) and Li/Mg-SST (1.03 ± 0.50 °C) while RMSE's between 1970 and 2012 are slightly higher (Table 3).

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The anomalies for the EU Sr/Ca-SST, Li/Mg-SST and Sr/Ca-Li/Mg-SST composite time series closely tracked the anomalies in the *in situ* air temperature data (Figs. 8a-c). Sr/Ca-SST and Sr/Ca-Li/Mg-SST performed slightly better than Li/Mg-SST ($r_{Sr/Ca} = 0.46$, $p < 0.001$, N = 189; $r_{Sr/Ca\text{-}Li/Mg} = 0.43$, $p < 0.001$, N = 189; $r_{Li/Mg} = 0.37$, $p < 0.001$, N = 189). Air temperatures showed marginally colder temperature anomalies between 1970 and 1978 compared to the Sr/Ca, Li/Mg or Sr/Ca-Li/Mg composite SST anomalies. AVHRR-OISSTv2 was also in close agreement with air temperature anomalies (Fig. 8d). ERSSTv4 anomalies mirrored air temperatures with overall slightly colder mean SST anomalies than in air temperatures, especially between 1970 and 1990 (Fig. 8e).

3.4 Regional and large-scale climate relationships

To assess regional correlations, we compared the EU Sr/Ca-SST composite with published coral proxy records from the Mozambique Channel and their corresponding instrumental data based on ERSSTv4 (Fig. 9; Fig. S9). The proxy records included *Porites* coral oxygen isotope and Sr/Ca from Mayotte (Comoros Archipelago; 13° S, 45° E; Zinke et al., 2008) in a lagoonal setting and from Ifaty Reef in a lagoon passage (Southwest Madagascar, 23° S, 43° E; Zinke et al., 2004). Bimonthly anomalies for ERSSTv4, Sr/Ca-SST and δ^{18}O-SST were calculated relative to the reference period 1973 to 1993. The ERSSTv4 records from the three sites, spanning 10° of latitude in the Mozambique Channel between 13° and 23° S, documented a statistically significant (>95%) warming trend since 1970 (Fig. 9). ERSSTv4 for 2° × 2° spatial grids near Europa and Ifaty Reef shared 98% of variability, while Mayotte shared 38% of variability with the former two sites. The coral proxy-based SST anomalies also showed statistically significant (>95%) warming trends, although generally higher than in ERSSTv4, with the exception of Ifaty that showed no trend in Sr/Ca-SST anomalies (Fig. 9).

The interannual variability in the EU Sr/Ca-SST composite anomalies and in the Mayotte and Ifaty proxy-SST anomalies fluctuated by ~±1 °C with the exception of a few warm and cold spikes in Mayotte and Ifaty time series which were not recorded at Europa (Fig. 9b to e; Fig. S10). The EU Sr/Ca-SST composite anomalies agreed best with interannual variability in Ifaty Sr/Ca-SST (r = 0.42, $p < 0.001$, N = 21) and δ^{18}O-SST (r = 0.19, $p < 0.050$, N = 21), although with a cold bias in Ifaty Sr/Ca between 1985 and 1995 (Fig. 9d and e; Fig. S10). The EU Sr/Ca-SST composite anomalies and Mayotte proxy-SST anomalies showed no

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We find no correlation between SST reconstructions or instrumental SST with either extension or calcification rates nor skeletal density in both cores (Fig. 8a). The period of fastest extension and highest calcification in EU3 corresponded to 1947 to 1961. No significant changes in extension or calcification rates were associated with known El Niño events (e.g. 1941/42 and 1998) or local cold/warm events recorded by instrumental and proxy records (e.g. 1994, 2002).

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significant correlations, although the trend estimates were within uncertainty bounds for Mayotte $\delta^{18}O$-SST (Fig. 9b and c; Fig. S10). Mayotte Sr/Ca-SST time series showed anomalous cold spikes between 1970 and 1978, which were not recorded in regional ERSSTv4 (Fig. S10b and c).

Spatial correlations between the EU composite SST anomalies and the AVHRR-OISSTv2 mean annual averages (July to June) between 1981 and 2012 (Fig. 10) for each grid point were calculated to investigate large-scale teleconnections. Similar spatial correlations were calculated with the AVHRR-OISSTv2 data near Europa at 22° S, 40° E (0.25° × 0.25° resolution) with the rest of the grid points (Fig. 10). The correlations of the detrended data were computed using the KNMI climate explorer (https://climexp.knmi.nl/; Trouet & Oldenborgh, 2005) with a cutoff p-value < 0.05. Similar correlation patterns were observed for the EU2/EU3 Sr/Ca-Li/Mg SST composite and the local AVHRR-OISSTv2 with global grids in AVHRR-OISSTv2 (Figs. 10a and b). Coherent positive correlation patterns emerge in the Mozambique Channel, the northern and southeastern Indian Ocean, the southeastern tropical Pacific and northern tropical Atlantic. The Sr/Ca and Li/Mg ratios showed the expected negative relationship of both proxies with regional AVHRR-OISSTv2 mirroring the SST patterns (Figs. 10c and d). Of particular interest was the strong relationship with the northern tropical Atlantic (0° N to 20° N, 80° W to 30° W).

The regressions of detrended coral composite Sr/Ca and Sr/Ca-Li/Mg combined SST reconstructions with northern tropical Atlantic AVHRR-OISSTv2 revealed the strongest positive relationships for annual means between July and June (Table 4). Correlations between detrended coral composite Li/Mg-SST reconstructions with northern tropical Atlantic AVHRR-OISSTv2 were slightly lower. Northern tropical Atlantic AVHRR-OISSTv2 (1981 to 1970) and ERSSTv4 (1970 to 2017) showed positive correlations with the Atlantic Multi-decadal Oscillation (AMO) index (r = 0.70 to 0.72, p < 0.001; Table 4). Our detrended coral composite Sr/Ca and Sr/Ca-Li/Mg combined SST reconstructions also showed statistically significant positive correlations with the AMO index based on ERSSTv4 (Table 4). However, AVHRR-OISSTv2 and ERSSTv4 for Europa indicated low or non-significant correlations with the AMO, respectively, despite the strong correlations with the northern tropical Atlantic (Table 3). Furthermore, the Tropical North Atlantic (TNA; Enfield et al., 1999) and North Tropical Atlantic indices (NTA; Penland & Matrosova, 1998) indicated statistically significant positive correlations with the coral-based SST and instrumental SST data at Europa (Fig. 10e; Table 4).

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The regressions of detrended seasonal averages in AVHRR-OISSTv2 for Europa with the Niño3.4 index of ENSO variability showed weak, yet statistically significant correlations in the season from February to April ($r = 0.47$; $p < 0.010$; Table 4). The correlations between ERSSTv4 and Niño 3.4 were weaker ($r = 0.34$, $p < 0.050$; Table 4). The detrended coral composite Sr/Ca, Li/Mg and their combined SST reconstructions showed no significant correlations with the Niño3.4 index. However, the Pacific/North American (PNA) pattern (Wallace & Gutzler, 1981), which is an atmospheric response to ENSO, showed statistically significant correlations with AVHRR-OISSTv2 ($r = 0.67$, $p < 0.001$) for Europa and the coral-derived SST anomalies between 1981 and 2012 ($r = 0.42$, $p = 0.014$; Table 4). The spatial correlation pattern of the PNA index with global AVHRR-OISSTv2 revealed a similar pattern as observed for the coral-based SST (Fig. 10).

4 Discussion

4.1 Reliability of Sr/Ca and Li/Mg as SST proxies

Both of the Europa coral core Sr/Ca and Li/Mg bimonthly time series (EU3 and EU2) showed highly significant correlations with the local and regional instrumental SST products (AVHRR-OISSTv2 and ERSSTv4). For the period of overlap between 2003 and 2012 both proxies performed equally well in core EU2 while core EU3 Li/Mg slightly underperformed Sr/Ca. The regression slopes with SST were within the range of published calibrations for *Porites* corals (e.g. Hathorne et al., 2013; Montagna et al., 2014; D'Olivo et al., 2018). The bimonthly Sr/Ca, Li/Mg and combined Sr/Ca-Li/Mg absolute SST reconstructions showed small deviations (mean RMSE's between 0.45 and 0.67°C; Table 3) from the instrumental temperatures with lower winter and slightly higher summer SST. For all proxies the agreement with instrumental data was highest for the period of overlap between cores (2003 and 2012). In general, AVHRR-OISSTv2 seasonal SST amplitudes and SST anomalies showed higher correlations with the coral-based SST reconstructions than with ERSSTv4. The lower temperatures in the proxy-SST compared with the satellite data of AVHRR-OISSTv2, which measures SST at the skin of the sea surface (top few millimeters), could be related to the living depth of the corals (8.5 to 9.5 m). This was particularly apparent in several cold spikes with 2S.D. (-0.72 °C) below the 1981 to 2012 mean SST in our coral-based SST anomaly reconstructions, which were also observed in the instrumental data (1971, 1972, 1976, 1978, 1980, 1984, 1986, 1994, 2001, 2008). The most extreme cold

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excursions during austral summer occurred in 1986, 1994, 2001 and 2008, which were also prominent in the AVHRR-OISSTv2. 1994 stands out as the coldest anomaly between 1970 and 2012 in coral-based SST (-1.34 °C), AVHRR-OISSTv2 (-1.37 °C) and ERSSTv4 (-1.16 °C). However, January/February 1989 and March-June 1997 cold spikes exceeding 1 °C observed in AVHRR-OISSTv2 were not as extreme in our coral-based SST anomalies (-0.58 °C in 1989; -0.1 °C in 1997). A possible explanation for these cold spikes is the upwelling of colder deeper water onto the north-east coast reef promoted by the steep slopes and topography of the fore-reef (gentle sloping plain to a depth of 25 m). Upwelling-related cold spikes have been recorded in temperature loggers across the Mozambique Channel at 18 m depth, potentially related to periods of active Mozambique Channel eddies interacting with the steep topography (Schouten et al., 2002; Van den Berg et al., 2007; Swart et al., 2010). Differences between the proxy records and the instrumental records at interannual scales could also reflect limitation in the instrumental records. The ERSSTv4 data used extending back to 1970 is based on very sparse observations in the ICOADS database for the southern Mozambique Channel. The resolution of the satellite data starting in 1981 should provide the best estimates for SST near Europa; however, observations near the coast can be susceptible to biases (e.g. mixing of land temperature with SST; Smit et al., 2013; Brevin et al., 2017). The comparison between AVHRR-OISSTv2 and local air temperature anomalies revealed an excellent agreement for the years covered by the weather station and serves as a quality check for the AVHRR-OISSTv2 data for our site. Nevertheless, the absolute temperature reconstruction from the coral Sr/Ca and Li/Mg ratios showed a good agreement with the different instrumental temperature datasets, especially for core EU2. Thus, both Sr/Ca and Li/Mg provide highly reliable SST proxies and in combination have the potential to improve SST reconstructions.

The statistically significant warming-trend of 0.58 ± 0.1 °C ($p < 0.001$) between 1970 and 2012 in the coral Sr/Ca-SST composite was in close agreement with instrumental SST data (0.47 ± 0.07 °C in ERSSTv4; 0.40 ± 0.18 °C in AVHRR-OISSTv2 since 1981). The Li/Mg-SST composite trend of 1.06 ± 0.15 °C ($p < 0.001$) is however too large, and inconsistent with both the Sr/Ca and instrumental records. The differences in warming trends in Li/Mg-SST and Sr/Ca-SST probably highlight the differences in incorporation between these elements (Montagna et al., 2014; Marchitto et al., 2018), which could be exacerbated during periods of thermal stress. The Li/Mg-SST anomalies were especially low during some years which resulted in a larger RMSE 0.67 ± 0.65 °C (Table 3) compared to Sr/Ca-SST and

AVHRR-OISSTv2, ERSSTv4, as well as local air temperatures. A potential limitation for the use of Li/Mg as SST proxy is the small number of studies to date reporting Li/Mg-SST relationships (regression slopes) in tropical *Porites* and *Siderastrea* corals (Hathorne et al., 2013; Montagna et al., 2014; Fowell et al., 2016; D'Olivo & McCulloch, 2017; D'Olivo et al., 2018; Marchitto et al., 2018). For example, applying the mean slope of -0.049 mmol/mol per °C for marine calcifiers reported in Montagna et al. (2014) to our Li/Mg data would lead to significant overestimations of SST anomalies, hence even larger cold biases. Applying the -0.097 mmol/mol per °C for Caribbean *Siderastrea siderea* forereef corals would underestimate SST anomalies (Fowell et al., 2016). The mean Sr/Ca-SST relationship of -0.060 mmol/mol per °C is, on the other hand, far better constrained by a much larger number of studies (e.g. Corrège 2006; De Long et al., 2012; Pfeiffer et al., 2017). In particular, EU3 Li/Mg was most likely affected by uncertainties in the incorporation of Mg and Li into the skeleton while EU2 Li/Mg showed no irregularities. Interestingly on a seasonal scale, Li/Ca and Mg/Ca in EU3 showed the expected negative correlation; however, on interannual to decadal scales these ratios were positively correlated. This perhaps reflects an "extreme" example of growth effects on Li and Mg unrelated to temperature (e.g. the effect of cation entrapment and heterogeneous distribution in the centres of calcification; Montagna et al., 2014; Marchitto et al., 2018). In most cases calculating Li/Mg cancels out this effect by leaving SST as the main controlling parameter; however, in core EU3 this appears not to be as effective, leading to slightly lower correlation of Li/Mg with SST compared to Sr/Ca with SST. Careful inspection of the sampling path along the major growth axes revealed that a potential cause for discrepancies in Li/Ca and Mg/Ca affecting Li/Mg might be due to suboptimal sampling along parallel growth axes as also apparent in Fowell et al. (2016). The overlap period of 2003 to 2012 was sampled continuously in both cores without switch in growth axis, showing an excellent agreement between cores including Li/Ca ($r = 0.57$, $p < 0.001$, $N = 54$) and Mg/Ca ($r = 0.58$, $p < 0.001$, $N = 54$). Prior to 2003, core EU3 was sampled along three different growth axes (1970 to 1982, 1983 to 1996 and 1996 to 2012) orientated at angles along the core length. Although all axes showed optimal growth orientations, the Li/Ca ratios in EU3 deviated from the trends shown in Mg/Ca, Sr/Ca and Li/Mg. The importance of optimal sampling along continuous main growth axes for optimal trace element ratios and stable isotope determinations has been shown in several recent studies (e.g. De Long et al., 2012; Zinke et al., 2016), which also appears to be the case for the Li/Mg proxy. This sensitivity of the Li and Mg proxies in core EU3, identified as *P. mayeri*, could also reflect a species effect due to slight differences in their calcification

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strategies. For example, D'Olivo *et al*., (2018) showed a deviation for *Porites solida* from other massive *Porites* species in the relationships between Sr/Ca and Li/Mg with temperature. However, this requires further investigations as this is the first long-term (multi-decadal) reconstruction based on massive *Porites*. Despite these uncertainties Li/Mg was overall the second-best performing proxy in this study with the detrended Li/Mg data showing an excellent agreement with the instrumental SST and Sr/Ca data. Furthermore, the interannual and decadal SST variations as well as spatial correlation patterns in the Li/Mg appeared not to have been affected and can be interpreted with high confidence as indicated by our field correlations. Overall the results from this study indicated that Sr/Ca is still superior to Li/Mg and was the most reliable SST proxy when applied to a longer time series. However, the excellent agreement between Sr/Ca and Li/Mg and their combination in core EU2 demonstrated that both SST proxies and their combination can provide with greater confidence, more reliable SST reconstructions with lower RMSEs (D'Olivo et al., 2018).

In addition, we tested the multiproxy paleothermometer based on Sr/Ca and Li/Mg data proposed by D'Olivo et al., (2018) in both corals. Using the proposed equations on cores EU2 and EU3 their respective RMSE values were 1.1 °C and 0.2 °C higher than the values obtained from a direct calibration against the SST products. While the multiproxy method produced excellent results for core EU3, the higher RMSE for EU2 could be explained by the limitations of the multiproxy method as solutions appear to deteriorate *for Porites solida* and corals with small effective tissue thickness (~ < 4 months). In this case EU2 had an effective tissue thickness of 3.9 months and was identified as *P. solida* while EU3 had an effective tissue thickness of 9.5 months and was identified as P. *mayeri*. This confirms the effectiveness of the multiproxy method proposed by D'Olivo et al., (2018) when applied within its limits.

4.2 Regional and large-scale climate teleconnections

The spatial correlations between Europa coral composite data and global SST data indicated a strong response to local variability in the Mozambique Channel at the latitude between 15 °S and 30 °S. The pattern of spatial correlation also suggested teleconnections with the northern/eastern Indian Ocean, the southeastern Pacific and the tropical Atlantic. ENSO influence in the instrumental data was weak and absent in our proxy records. Only the warmest years (summer maxima) of the Europa composite time series corresponded with

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strong El Niño (1998, 2010) and La Niña (1999, 2000, 2011) events, as attested for example by the high coral mortality reported from 1998 (Quod & Garnier, 2004) and the moderate coral bleaching observed in 2011 (Guillaume & Bruggemann, 2011). Local air temperatures and AVHRR-OISSTv2 anomalies indicated other warm years (>0.5 °C) corresponding to El Niño years (1983, 1988, 1991/92), La Niña years (1989, 1996) and ENSO neutral years (1981, 2007, 2012/13). The majority of these lower magnitude warm events were also recorded in the coral proxy time series. Overall these results suggest a weak or variable impact of ENSO around Europa.

Perhaps the most interesting and to some extent unexpected relationship of our study region was found with the northern tropical Atlantic (5 °N to 20 °N, 30 °W to 80 °W), a region that corresponds with the main development region for Hurricanes in the tropical Atlantic (Knutson et al., 2010). This region also has strong relationships with the AMO, which is the leading mode of multi-decadal variability in the northern Atlantic and thought to be driven by Atlantic Meridional Ocean Circulation (AMOC) variability (e.g. Schlesinger & Ramankutty, 1994; Kerr, 2000; Knight et al., 2005). Our coral-based SST reconstructions and satellite data revealed a strong relationship with both the Tropical North Atlantic (TNA; Enfield et al., 1999) and North Tropical Atlantic indices (NTA; Penland & Matrosova, 1998) as well as the AMO since at least 1970 (Table 4). However, the ERSSTv4 for Europa showed non-significant correlations with the AMO, while the relationship with the northern tropical Atlantic SST was robust. The exact mechanism for this teleconnection between the Mozambique Channel and the tropical Atlantic remains elusive. We speculate that atmospheric processes in response to AMO, tropical Atlantic or Indo-Pacific variability might be controlling this relationship since all correlated regions lie within or near the trade wind convergence zone (the Intertropical Convergence Zone) where atmospheric circulation associated with deep convection controls underlying SST (Schott et al., 2009; Xie et al., 2010; Marshall et al., 2014; Green et al., 2017; Koseki & Bhatt, 2018). Wind-driven upwelling controls the regions with positive correlations (negative with the geochemical proxies) in the northern and eastern Indian Ocean, the northern South China Sea and the southeastern Pacific (Schott et al., 2009; Xie et al., 2009; Varela et al., 2015; Sydeman et al., 2014). The strongest resemblance to an atmospheric pattern driving the observed SST pattern, including teleconnections with the Mozambique Channel, was found with the Pacific/North American (PNA) pattern (Trenberth et al., 1998). The PNA is one of the strongest modes of low-frequency atmospheric variability in the Northern Hemisphere with

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an equivalent Pacific/South American pattern in the Southern Hemisphere (Mo & Peagle, 2001; Irving & Simmonds, 2016). The PNA/PSA pattern is strongly influenced by ENSO and the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), tending towards being in its positive phase during El Niño and negative phase during La Niña (Rodionov & Assel, 2001). The importance of atmospheric processes for Indo-Pacific climate teleconnections emanating from the Pacific PNA and PSA patterns has been documented in several studies (Rodionov & Assel, 2001; Dai et al., 2017). The Mozambique Channel and adjacent southern Africa are both impacted by PNA/PSA variability (Blamey et al., 2018). Therefore, our spatial correlation between the TNA, NTA, PNA and global SST point towards tropical-extratropical atmospheric forcing of the observed SST teleconnection patterns in our study.

5 Conclusions

A comparison of multiple trace element ratios in two *Porites* cores from Europa (southern Mozambique Channel) indicated that Sr/Ca was the most robust paleothermometer analysed. In addition to Sr/Ca, Li/Mg and their combination showed great potential for improved higher confidence multi-element SST reconstructions. The SST over the last 42 years (1970 to 2012) was dominated by interannual variability with a warming trend of 0.58 ± 0.1 °C in Sr/Ca-SST in close agreement with instrumental data (0.47 ± 0.07 °C). Li/Mg and the combination of Li/Mg and Sr/Ca showed unrealistically large warming trends, most probably caused by uncertainties around Li/Ca and Mg/Ca incorporation with marginally different uptake mechanisms for these trace elements. However, detrended data from Sr/Ca, Li/Mg and the combination of Li/Mg and Sr/Ca agreed well with each other and with regional instrumental SST and local air temperature. Spatial correlations between detrended Sr/Ca, Li/Mg and combined proxies with instrumental SST at Europa revealed robust correlations with local climate variability in the Mozambique Channel and teleconnections to regions in the tropical Atlantic Ocean, Indian Ocean and southeastern Pacific where surface wind variability appeared to dominate the underlying SST. Of particular interest is the strong correlation found between the proxy and instrumental SST records with the northern tropical Atlantic SST. Only a weak correlation was found with ENSO, with recent warm anomalies in the geochemical proxies coinciding with strong El Niño or La Niña. We identified the PNA atmospheric pattern, which develops in the Pacific in response to ENSO, and the tropical North Atlantic SST as the most likely causes of the observed teleconnections with the Mozambique Channel SST. In conclusion, the Europa *Porites* sp. geochemical records highlight the great potential of Sr/Ca and Li/Mg ratios as accurate, reliable high-resolution climate archives for the tropical oceans.

6 Data availability

Trace element data will be made publicly available on the NOAA's WDC paleoclimate data server https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets.

7 Author contribution

JZ, MMMG, JHB, JCG and JPD designed the study and lead the writing of the manuscript. MMMG provided the samples, JZ, JPD and MMMG organised and performed the trace element analysis, while JML did the coral densitometry measurements. All co-authors contributed to analysis and writing of the manuscript.

8 Acknowledgments

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Tables

Location	Latitude (S)	Longitude (E)	Depth (m)	Core #	Length	Mean Extension $mmyr^{-1}$	Collection dates
North Reef	22°19.839	40°21.758	12.80	EU-2	105	1.07±0.19	2/5/2013
North-East Reef	22°20.119	40°23.333	12.00	EU-3	136	1.20±0.27	3/5/2013

Table 1 – Coral core GPS locations from Europa, water depth, core name, core length, mean extension rate between 1968 and 2012 (standard deviation in brackets) and collection dates.

core	proxy	SST product	slope	Conf. interval	intercept	Conf. interval	r^2	r^2 adj.	SSE	RMSE	DoF	Period
EU2	Sr/Ca	AVHRR-OISSTv2	-0.045	0.003	10.241	0.083	0.93	0.94	0.021	0.02	53	2003-2012
		ERSSTv4	-0.051	0.004	10.395	0.100	0.93	0.93	0.023	0.021	53	2003-2012
	Li/Mg	AVHRR-OISSTv2	-0.045	0.003	2.672	0.088	0.93	0.93	0.023	0.021	53	2003-2012
		ERSSTv4	-0.051	0.004	2.815	0.115	0.91	0.91	0.030	0.024	53	2003-2012
EU3	Sr/Ca	AVHRR-OISSTv2	-0.040	0.003	9.974	0.083	0.92	0.92	0.020	0.019	53	2003-2012
		ERSSTv4	-0.046	0.004	10.117	0.093	0.92	0.92	0.020	0.019	53	2003-2012
	Li/Mg	AVHRR-OISSTv2	-0.052	0.007	2.739	0.200	0.78	0.78	0.119	0.047	53	2003-2012
		ERSSTv4	-0.060	0.009	2.927	0.226	0.78	0.78	0.119	0.047	53	2003-2012
	Sr/Ca	AVHRR-OISSTv2	-0.042	0.002	10.049	0.064	0.86	0.86	0.138	0.027	184	1981-2012
		ERSSTv4	-0.048	0.002	10.191	0.058	0.88	0.88	0.179	0.027	252	1970-2012
	Li/Mg	AVHRR-OISSTv2	-0.057	0.004	2.898	0.117	0.77	0.77	0.452	0.049	184	1981-2012
		ERSSTv4	-0.064	0.004	3.076	0.108	0.78	0.78	0.612	0.049	252	1970-2012

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Table 2 – Robust linear regression equations (weighted least squares) for core EU2 and EU3 Sr/Ca and Li/Mg ratios with AVHRR-OI SSTv2 and ERSSTv4. Conf. interval= 95% confidence interval of the regression slopes and intercepts; r^2 adj.= r^2 adjusted; SSE= Standard Error; RMSE= Root Mean Square Error; DoF= degrees of freedom (N-2).

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	Individual proxies RMSE and SD					
Core ID	**Sr/Ca**	**Li/Mg**	**Mg/Ca**	**Li/Ca**	**Sr/Ca-Li/Mg**	**Period**
EU2	0.38	0.36	1.13	0.58	0.32	2003-2012
EU3	0.41	0.90	1.79	1.65	0.60	2003-2012
EU3	0.55	0.74	1.33	1.41	0.62	1981-2012
Avg. all	**0.45**	**0.67**	**1.42**	**1.21**	**0.51**	1981-2012

Table 3 – Root mean square error (RMSE) for trace element ratios against AVHRR-OISSTv2 for individual trace element ratios and Sr/Ca-Li/Mg combination. Period used for calculation of RMSE indicated in last column.

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	Northern Tropical Atlantic SST	AMO Index	TNA/NTA	Niño3.4
#EU-AVHRR-OISSTv2	0.59***	0.37**	0.55***/ 0.53***	0.47** (FMA)
^EU-ERSSRv4	0.37**	0.18	0.34**/ 0.36**	0.34** (JFMA)
^EU-composite Sr/Ca SST anomalies	0.61***	0.46***	0.53***/ 0.45**	-
^EU-composite Li/Mg SST anomalies	0.55***	0.54***	0.40** / 0.32*	-
^EU-composite Sr/Ca-Li/Mg SST anomalies	0.60***	0.52***	0.47***/ 0.39**	-

#1981-2013; ^1970-2013; *=90%, **=95%, ***=99% significance; DoF= 40 (N-2).

Table 4 – Linear correlation of detrended, mean annual instrumental and coral composite proxy-based SST for Europa (EU) with northern tropical Atlantic SST, the AMO index based on ERSSTv4, the Tropical North Atlantic (TNA; Enfield et al., 1999) and North Tropical Atlantic index (Penland & Matrosova, 1998) and the seasonal Niño3.4 index between 1970 and 2012 (Kaplan et al., 1998).

Figure captions

Figure 1 - Coral collection sites for cores EU2 and EU3 along the northern-northeastern reef slope of Europa and its positioning within the southern Mozambique Channel (south-west Indian Ocean).

Figure 2 - Mean annual coral growth parameters of cores EU3 and EU2 compared to coral composite Sr/Ca-SST reconstruction, AVHRR-OISSTv2 (Banzon et al., 2016) and ERSSTv4 (Liu et al., 2015). Mean annual a) EU2 and EU3 linear extension rate (CoralXDS and Sr/Ca-derived), b), skeletal density (CoralXDS) c) calcification rate (CoralXDS and Sr/Ca-derived) and d) SST time series (ERSSTv4, AVHRR-OISSTv2; EU Sr/Ca-SST composite).

Figure 3 - Bimonthly interpolated time series of trace element/Ca proxies from cores EU2 and EU3. a) Sr/Ca, b) Li/Mg, c) Mg/Ca and d) Li/Ca.

Figure 4 – Scatter plot of bimonthly trace element ratios in cores EU2 (black dots) and EU3 (blue dots) over the full length of the records (EU2: 2002-2012; EU3: 1970-2012). a-c) Sr/Ca ratios vs. Li/Mg, Mg/Ca and Li/Ca, d-e) Li/Mg vs. Mg/Ca and Li/Ca and f) Li/Ca vs. Mg/Ca. The 95% prediction intervals of the regressions are indicated by red dashed (EU3) and green solid lines (EU2) and linear fits for each core with a red line. Regression equations are provided in Table S1.

Figure 5 - Linear regressions of TE/Ca proxies with AVHRR-OISSTv2 (Banzon et al., 2016) for core EU3 1981-2012 (a,c) and EU2 2003-2012 (b,d). The TE/Ca records were calibrated using the respective linear regression equations of the bimonthly correlations obtained for each of the core records from the two sites. The 95% confidence intervals of the regressions are indicated. Regression equations are provided in Table 2.

Figure 6 - Absolute SST reconstructions for cores EU3 (red) and EU2 (blue) with SST residuals based on the calibration period 1981 to 2012 for a) Sr/Ca-SST, b) Li/Mg-SST and c) their combination in comparison to AVHRR-OISSTv2 (Banzon et al., 2016; black) and *in*

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situ SST (orange; 2009-2010). d) residuals for Sr/Ca-SST, Li/Mg-SST and their combination for cores EU2 and EU3 with respect to the AVHRR-OISSTv2 data (Banzon et al., 2016).

Figure 7 - SST anomaly reconstructions with SST residuals for a) EU composite Sr/Ca, b) EU composite Li/Mg and c) their combination for cores EU2 and EU3. d) residuals for SST anomalies of Sr/Ca-SST, Li/Mg-SST and their combination for cores EU2 and EU3 with respect to the AVHRR-OISSTv2 data (Banzon et al., 2016). Anomalies were calculated relative to the 1981 to 2010 average bimonthly seasonal cycle.

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Figure 8 - Comparison of coral composite Sr/Ca-SST, Li/Mg-SST and Sr/Ca-Li/Mg-SST anomaly reconstructions with air temperature from Europa Météo-France weather station data. a) Sr/Ca-SST composite, b) Li/Mg-SST composite, c) Sr/Ca-Li/Mg-SST composite, d) Europa gridded AVHRR-OISSTv2 (Banzon et al., 2016) and e) Europa gridded ERSSTv4. Anomalies were calculated relative to the 1981 to 2010 average bimonthly seasonal cycle for proxy reconstructions, instrumental SST and air temperatures.

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Figure 9 - Regional comparison of Mozambique Channel ERSSTv4 anomalies for Mayotte (green), Europa (orange) and Ifaty Madagascar (blue) in a) with linear warming trends in brackets. EU Sr/Ca-SST composite anomaly compared with b) Mayotte δ^{18}O-SST anomaly (blue), c) Mayotte Sr/Ca-SST anomaly (blue), d) Ifaty δ^{18}O -SST anomaly (blue) and e) Ifaty Sr/Ca-SST anomaly (blue). Anomalies were calculated for the 1973 to 1993 reference period. Linear warming trends indicated in b) to e) for proxy-SST for individual record length with EU composite Sr/Ca-SST anomaly only indicated once in panel b. Proxy data taken from Zinke et al. (2004, 2008).

Figure 10 - Spatial correlations of proxy-based coral composite SST reconstructions with local and global AVHRR-OISSTv2 for mean annual data (Banzon et al., 2016). a) local AVHRR-OISSTv2 with global AVHRR-OISSTv2, b) local AVHRR-OISSTv2 with EU composite Sr/Ca-Li/Mg-SST, c) local AVHRR-OISSTv2 with EU composite Sr/Ca ratios and d) local AVHRR-OISSTv2 with EU composite Li/Mg ratios. Panels e and d show spatial correlations of the TNA and PNA indices with global AVHRR-OISSTv2. Only correlations with p<0.05 were coloured.

Figures

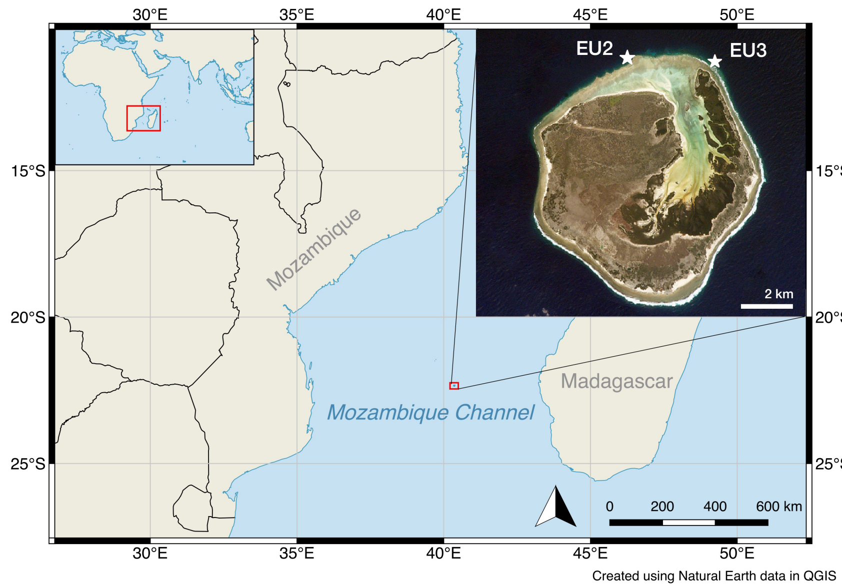

Figure 1 - Coral collection sites for cores EU2 and EU3 along the northern-northeastern reef slope of Europa and its positioning within the southern Mozambique Channel (south-west Indian Ocean).

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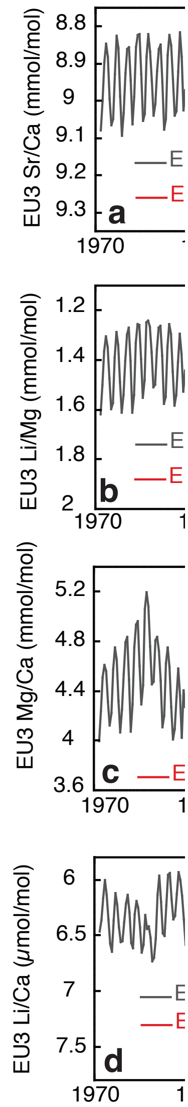

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Deleted: Fig 2 Bimonthly interpolated time series of trace element/Ca proxies from cores EU3 and EU2. a) Sr/Ca, b) Li/Mg, c) Mg/Ca, d) Li/Ca.

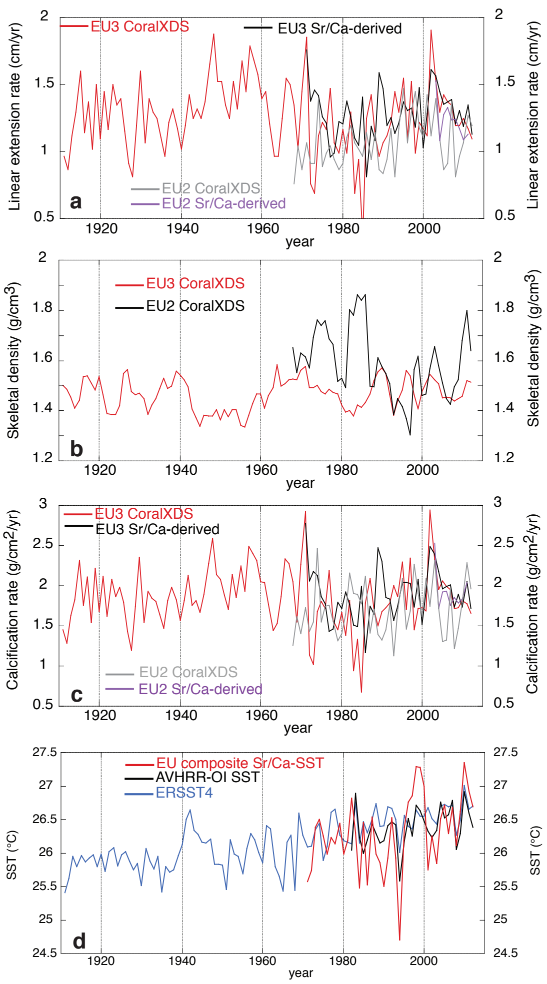

Figure 2 - Mean annual coral growth parameters of cores EU3 and EU2 compared to coral composite Sr/Ca-SST reconstruction, AVHRR-OISSTv2 (Banzon et al., 2016) and ERSSTv4 (Liu et al., 2015). Mean annual a) SST time series, b) EU2 and EU3 linear extension rate (CoralXDS and Sr/Ca-derived), c) skeletal density (CoralXDS) and d) calcification rate (CoralXDS and Sr/Ca-derived).

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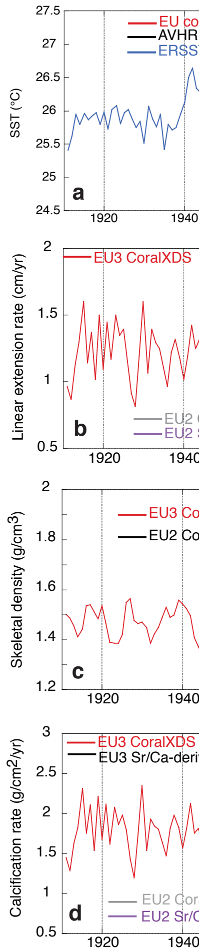

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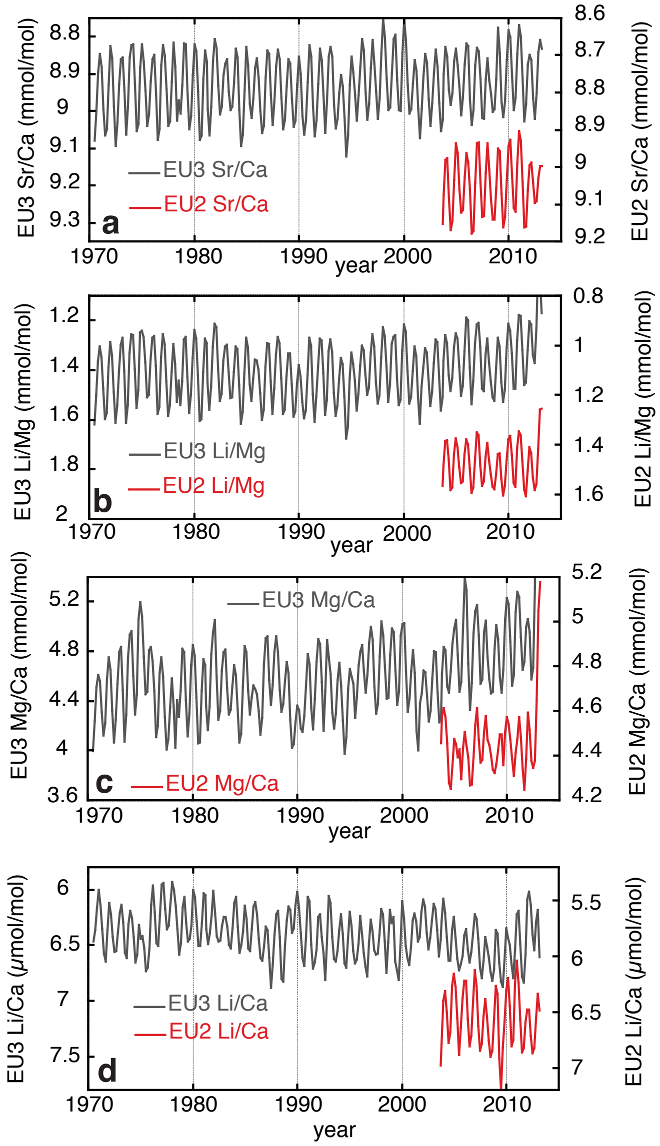

Fig 3 - Bimonthly interpolated time series of trace element/Ca proxies from cores EU3 and EU2. a) Sr/Ca, b) Li/Mg, c) Mg/Ca, d) Li/Ca.

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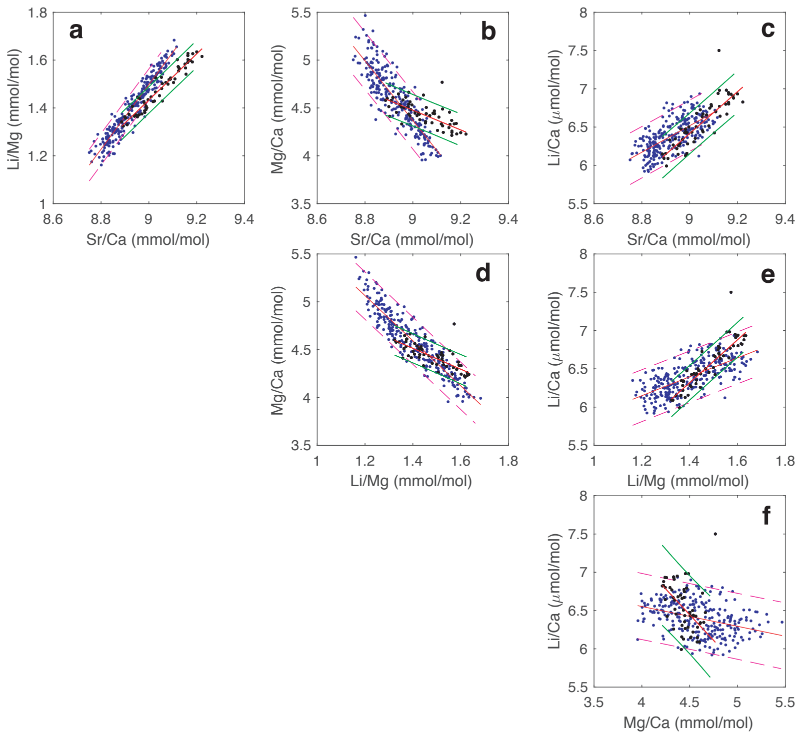

Figure 4 – Scatter plot of bimonthly trace element ratios in cores EU2 (black dots) and EU3 (blue dots) over the full length of the records (EU2: 2002-2012; EU3: 1970-2012). a-c) Sr/Ca ratios vs. Li/Mg, Mg/Ca and Li/Ca, d-e) Li/Mg vs. Mg/Ca and Li/Ca and f) Li/Ca vs. Mg/Ca. The 95% prediction intervals of the regressions are indicated by red dashed (EU3) and green solid lines (EU2) and linear fits for each core with a red line. Regression equations are provided in Table S1.

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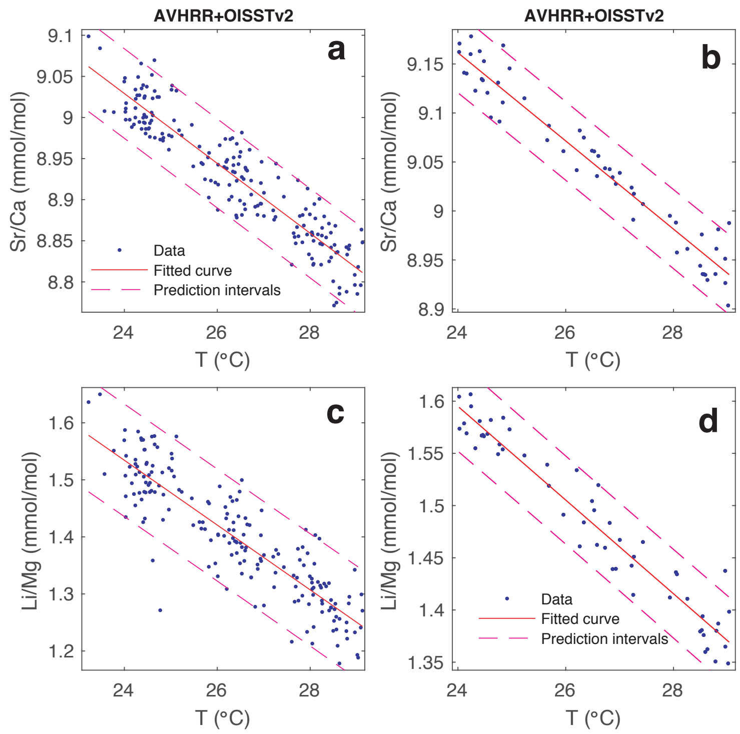

Figure 5 - Linear regressions of TE/Ca proxies with AVHRR-OISSTv2 for core EU3 1981-2012 (a,c) and EU2 2003-2012 (b,d). The TE/Ca records were calibrated using the respective linear regression equations of the bimonthly correlations obtained for each of the core records from the two sites. The 95% confidence intervals of the regressions are indicated. Regression equations are provided in Table 2.

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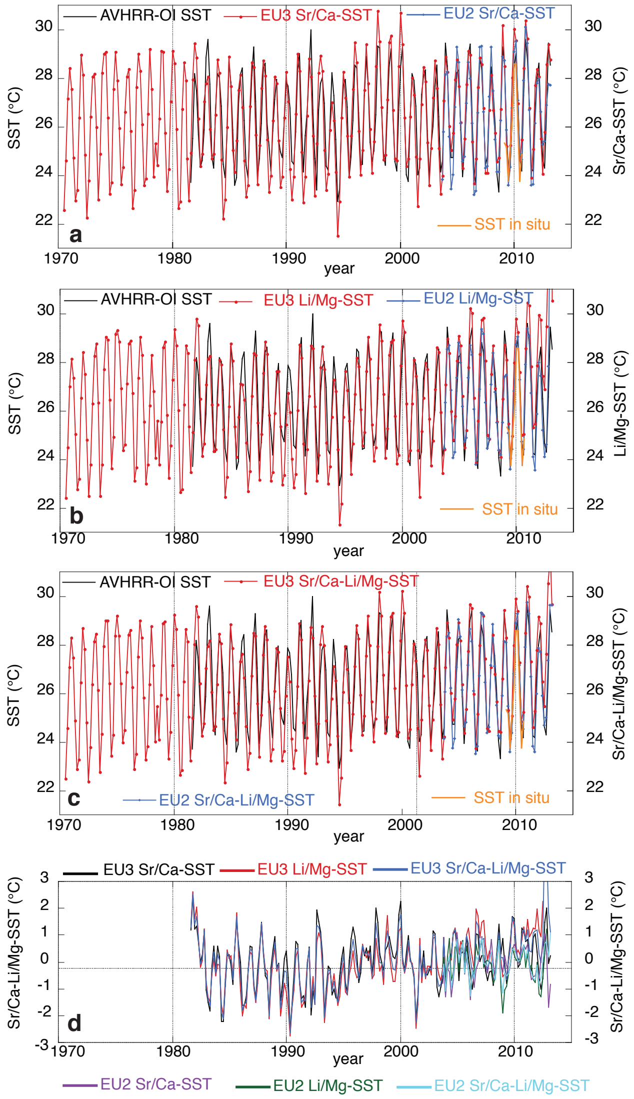

Figure 6 - Absolute SST reconstructions for cores EU3 (red) and EU2 (blue) with SST residuals based on the calibration period 1981 to 2013 for a) Sr/Ca-SST, b) Li/Mg-SST and c) their combination in comparison to AVHRR-OISSTv2 (Banzon et al., 2016; black) and *in situ* SST (orange; 2009-2010). d) residuals for Sr/Ca-SST, Li/Mg-SST and their combination for cores EU2 and EU3 with respect to the AVHRR-OISSTv2 data.

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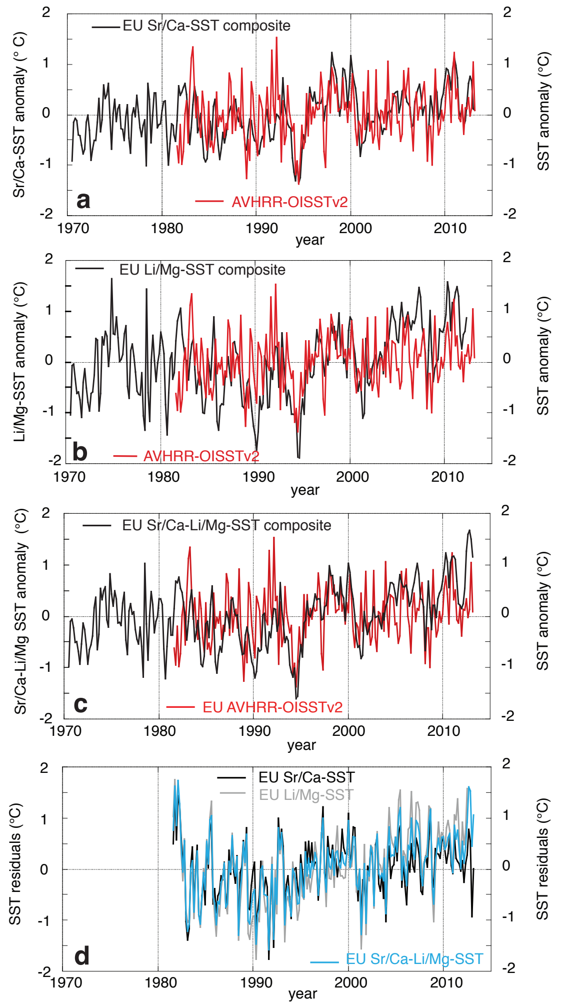

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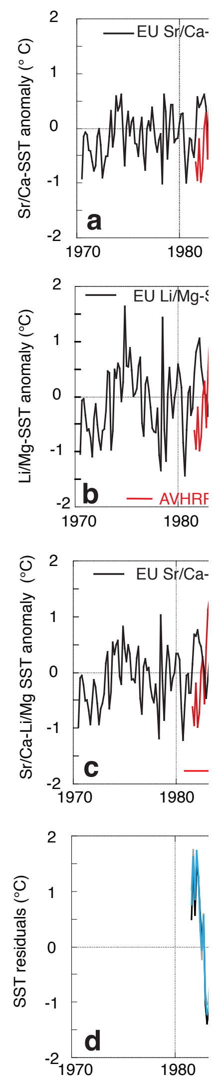

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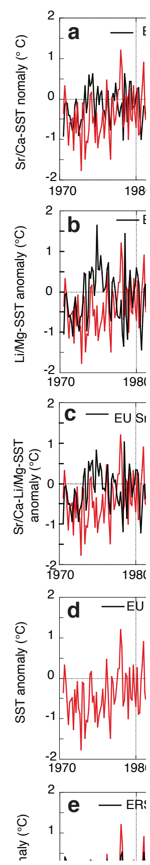

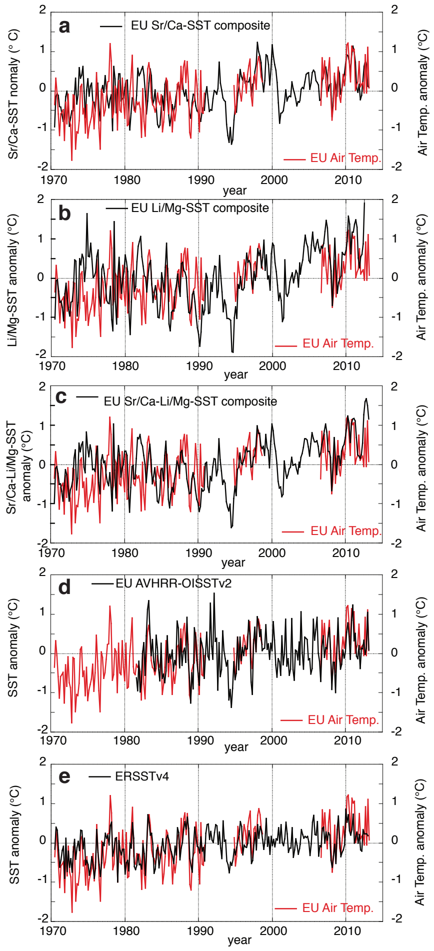

Figure 8 - Comparison of Europa (EU) coral composite Sr/Ca-SST, Li/Mg-SST and Sr/Ca-Li/Mg-SST anomaly reconstructions with air temperature (AT) from Europa Météo-France weather station data. a) Sr/Ca-SST composite, b) Li/Mg-SST composite, c) Sr/Ca-Li/Mg-SST composite, d) Europa gridded AVHRR-OISSTv2 (Banzon et al., 2016) and e) Europa gridded ERSSTv4 (Liu et al., 2015). Anomalies were calculated relative to the 1981 to 2010 average bimonthly seasonal cycle for proxy reconstructions, instrumental SST and air temperatures.

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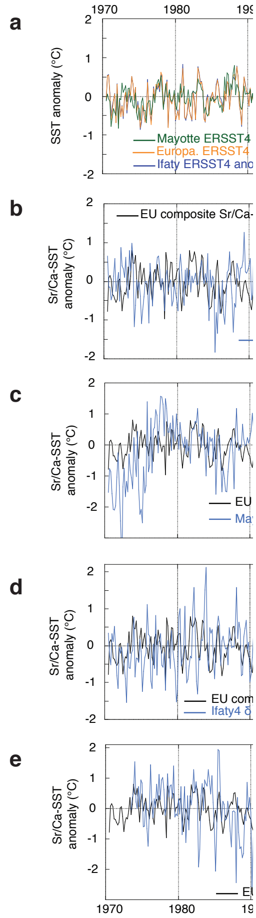

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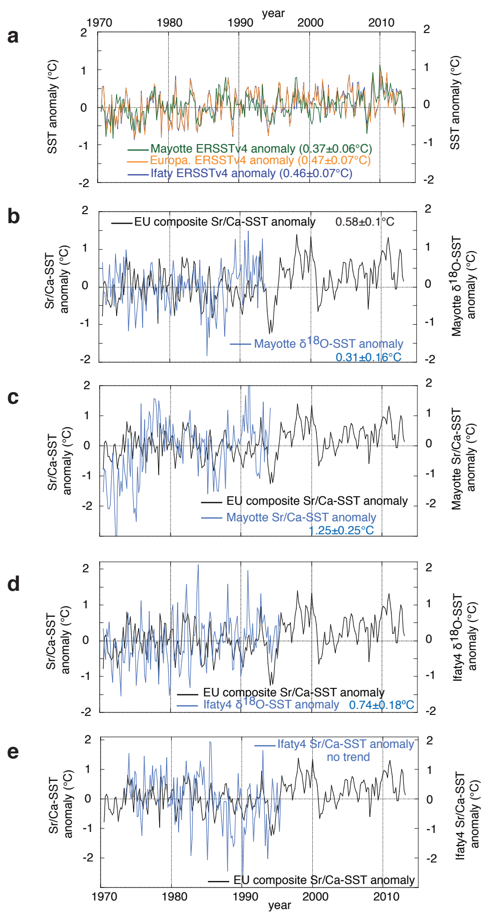

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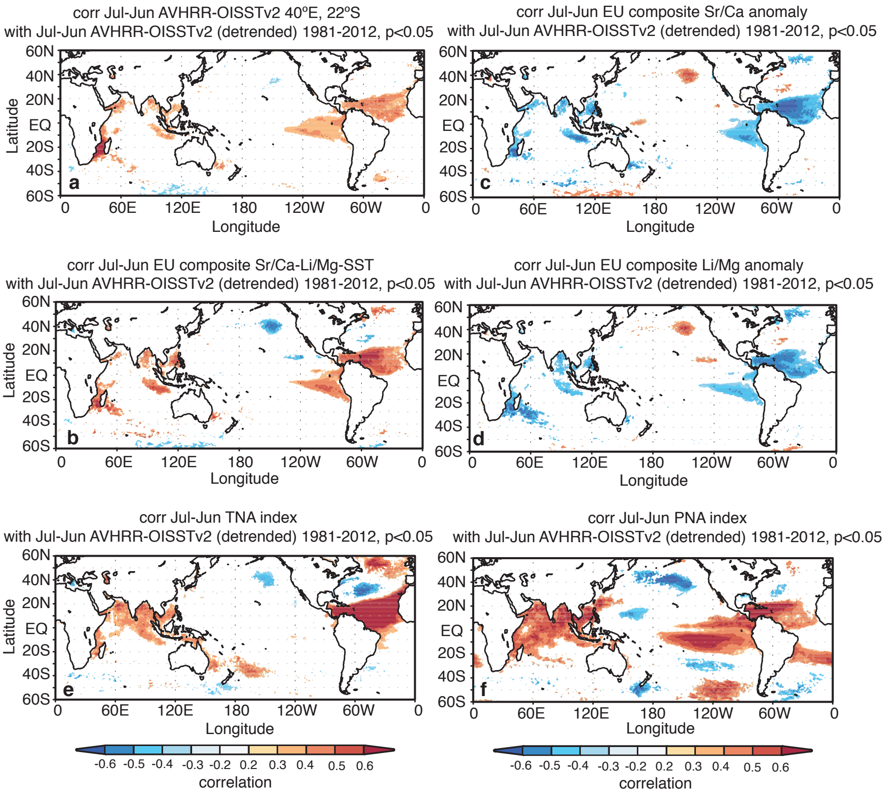

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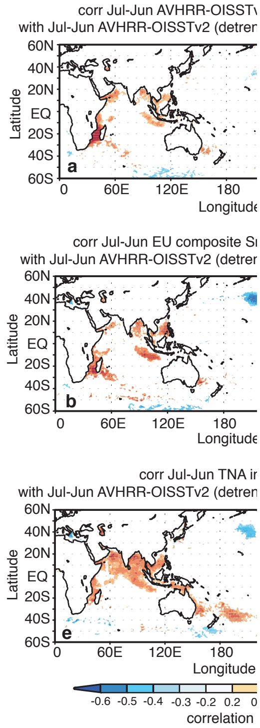

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