Authors’ response to reviews of

"Nutrients attenuate the negative effect of ocean acidification on reef coral calcification in the Arabian Sea upwelling zone (Masirah Island, Oman)"

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RC: Reviewers’ comment AR: Authors’ response

1. Introduction:

on behalf of my co-authors, I would like to thank the reviewers for commenting on our manuscript. Their supporting comments and ideas are important for us to improve the significance of our work.
Given that both reviewers stated fundamental concerns about the framing and interpretation of our data, I would like to address these general aspects in advance, before discussing the single reviewer comments in detail.
The reviewers express general doubts about the reliability of the mean annual calcification data (extension rate and bulk density) of *Porites* from Masirah Island reported by us because of a comparatively small number of replicates (n=3). Accordingly, low mean annular skeletal bulk density and enhanced linear extension rate of *Porites* from Masirah Island recorded by our study relative to those of *Porites* from the Indo-Pacific is suggested to be a possible artefact of a small database. However, a larger number of specimens and respective calcification data is available to us. This supplementary information was provided to the open discussion in a reply to RC1 (16 Sept 2021). The dataset clearly shows that the calcification data presented in our discussion paper are not biased by poor statistics, but document a mean situation for the region. We selected three out of the six samples for further geochemical analysis (laser ICP-MS) that were considered representative for the site studied. These geochemical analyses enabled us to obtain monthly resolved calcification patterns of *Porites* from a region affected by intense seasonal upwelling, which is indeed a novel approach. We will therefore keep the focus on these three samples also in the revised version of the manuscript. However, as no *Porites* growth data exists from the Arabian Sea, the entire data of all 6 specimen will be added to the revision as an electronic supplement. In this way, we hope to encourage further *Porites* growth studies in a hitherto unexplored region of the western Indian Ocean.
Being aware that the number of three samples is statistically problematic, we will re-arrange the manuscript as suggested by both reviewers and place the focus more on a combination of the proxy data (e.g. Li/Mg, Ba/Ca) and intra-annual growth patterns presented in the original manuscript. To investigate the influence of upwelling on coral calcification, we discuss differences between the seasonal growth patterns within our samples, in particular those observed during the upwelling and non-upwelling seasons. By doing so, "intra-reef variabilities" in coral growth problematized by Reviewer 2 are largely negligible, as local factors and the genotype remain constant within a single specimen. We strongly feel discussing the existing data in this way is scientifically more robust and solves any legitimate concerns of the reviewers.

2. Reviewer # 1 (RC1):

2.1. *“Three replicate cores is just not enough to have robust statistics…Actually, the only way I see forward for the authors (besides getting more corals) is to completely re-frame the study based on the geochemistry.”*

AR: This comment is addressed in detail in the introduction.

2.2. *“I had no idea there was going to be Li/Mg geochemistry in this study based on the title and abstract.”*

AR: Information on the application of Li/Mg and Ba/Ca trace element analyses for the interpretation of intra-annual patterns of coral calcification will be provided in the revised version of the abstract.

2.3. *“I don't think it makes sense to compare the growth rates to just the GBR.”*

AR: In the discussion paper, we compare our growth data from Masirah Island with reference data from the GBR (29 sites, 245 colonies) and from Hawaii (14 sites, 140 colonies) (Grigg, 1981; Lough and Barnes, 2000). These two datasets represent the largest of their kind for *Porites*. The calcification variables (skeletal density, extension rate and calcification rate) are all significantly correlated with SST (Lough and Barnes, 2000). For this reason, the regressions of these relationships are frequently used as "baselines" for estimating the performance of recent and fossil *Porites* with regard to their bulk density, extension rates and calcification rate at a certain SST (Brachert et al., 2016; Brachert et al., 2020; Lough et al., 2016; Manzello et al., 2014). However, we agree that our approach of applying the regressions from the Indo-Pacific reference dataset to predict calcification performance of *Porites* from the Arabian Sea possibly overstresses the global validity of the causal relationship between SST and calcification because of a small sample number of specimens in our dataset (n = 3). For this reason, in our revised manuscript, we refrain from predicting "theoretical values" for the calcification variables from a given SST and instead provide a more qualitative comparison of our data with published *Porites* growth data. In this way, we will provide a more global perspective, by showing additional (published) *Porite*s growth data from Thailand, Western Australia, the Gulf of Mexico plus three other regions affected by upwelling, in addition to the previously presented data from the GBR and Hawaii. All published records from globally distributed upwelling sites show a conspicuous and consistent pattern of low skeletal density without any exception (Fig.1).

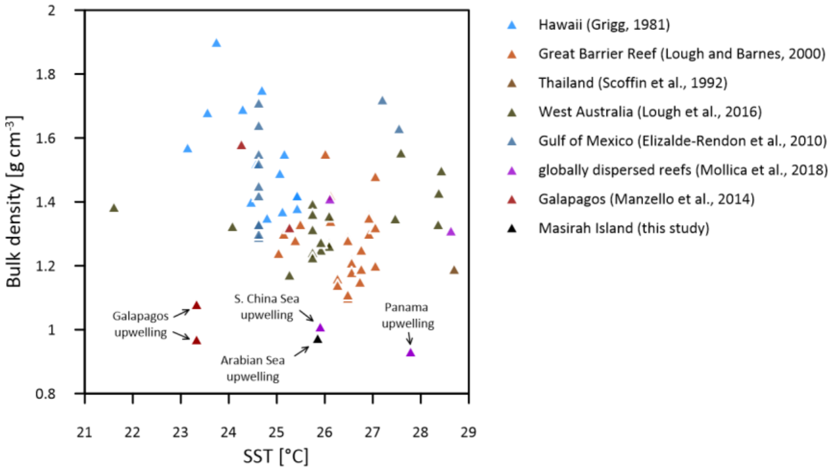

Figure 1: Annual means in *Porites* skeletal bulk density versus annual sea surface temperature (SST) from various Indo-Pacific and Western Atlantic reef sites. Note that all reef sites affected by seasonal upwelling show exceptionally low skeletal bulk density.

3. Reviewer # 2 (RC2):

Concerns:

3.01. *"Overall, an n of 3 is fairly small to make these growth assumptions with… growth is highly variable across locations and genotypes and thus would require a higher n to make stronger predictions/*estimates."

AR: This comment is addressed in detail in the introduction.

3.02. *"Coral growth is reliant on a lot of different biological processes that are largely ignored throughout this text. While calcifying fluid is discussed, the authors never actually make these measurements. Further, the authors ignore how much variability in coral growth there is within a genus or even a species and over-estimate the reliance of growth on SST. The authors should consider what other factors can impact the variability across their cores and work to put it more in the context of the biology of corals. Along these same lines, coral cores collected from the Pacific may not experience similar environmental conditions and may likely have different populations/species of Porites corals, thus comparison of the corals from this study with Pacific corals should be made with caution."*

AR: This reviewer comment will be split into three sections, which will be answered separately in the following:

"Coral growth is reliant on a lot of different biological processes that are largely ignored throughout this text."

AR: We are working on dead coral material and do not want to speculate about the biological processes in detail, but rather discuss coral calcification with respect to environmental controls. In this context, we strongly feel to address fundamental environmental factors such as SST, pH, Ω_{Arag} and nutrients which have been shown to have the greatest impact on reef coral calcification (Courtney et al., 2017; Ross et al., 2019).

„*While calcifying fluid is discussed, the authors never actually make these measurements."*

AR: Indeed, we did not perform combined analyses of B/Ca and $\delta^{11}B$ on our specimens in order to estimate the Ω_{cf} of the calcification fluid. Recent publications, however, have led us to consider Ω_{cf} as a major parameter controlling skeletal density (Mollica et al., 2018). Considering this, it is essential for us to discuss the variability in skeletal density with regard to possible influences of Ω_{cf}. Systematic measurements of B/Ca and $\delta^{11}B$ are currently underway in the frame of a cooperation beyond the group of co-authors for this manuscript.

"Further, the authors ignore how much variability in coral growth there is within a genus or even a species and over-estimate the reliance of growth on SST. Along these same lines, coral cores collected from the Pacific may not experience similar environmental conditions and may likely have different populations/species of Porites corals, thus comparison of the corals from this study with Pacific corals should be made with caution"

AR: An overwhelming number of studies demonstrate SST to have the most significant impact on reef coral calcification (Courtney et al., 2017; Lough and Barnes, 2000; Lough, 2008; Lough et al., 2016). For this reason, we do not agree with the statement of having overestimated the reliance of growth on SST. However, as we already mentioned in our response to RC1-2.3, we agree that our approach of applying the regressions from the Indo-Pacific reference dataset to predict calcification performance of *Porites* from the Arabian Sea likely poses problems. This is because of a small number of replicates (n = 3), which means that we are likely unable to capture possible full growth variability at Masirah Island. To overcome this, we decided to refrain from calculating theoretical calcification based on the regressions from Indo-Pacific *Porites* but rather to focus on the intra-annual growth variability between the upwelling season and the non-upwelling season at Masirah Island. Intra-annual growth variability within a single specimen is now being discussed in terms of the coral's calcification response to seasonally changing environmental factors such as SST, Ω_{Arag}, light availability for photosynthesis and seawater nutrients, while growth variability across our samples is also discussed with regard to locational- and inter-species variability.

3.03. *"While the satellite SST matched very well with in situ SST measurements, the other satellite phosphate and nitrate parameters were not similarly grounded in truth. Further, the lower resolution for these satellite products is concerning since nutrient values can be highly variable across a spatial gradient."*

AR: WOA18 nutrient data is not a satellite product, but a generalized interpolation of all available in-situ observations performed within each 1° square (Garcia et al., 2018). Due to reframing of our study with a new focus on intra-annual growth patterns, we only consider monthly resolved WOA18 nutrient data from Masirah Island in the revised version of the manuscript (Fig.2, discussion paper). These data show relatively homogeneous nutrient concentrations during the non-upwelling season and a pronounced maximum of both essential nutrients (phosphate, nitrate) during the upwelling season. This intra-annual dynamic of nutrient concentrations is generally associated with upwelling areas and has also been observed in the northern Arabian Sea through in-situ observations (Currie et al., 1973; Savidge et al., 1990). In combination with the excellent agreement to skeletal Ba/Ca records, we assume that the general pattern of monthly resolved WOA18 nutrient concentrations at Masirah Island qualitatively reflect the intra-annual nutrient cycle of surface waters (Lea et al., 1989; Montaggioni et al., 2005; Tudhope et al., 1996). Nevertheless, we are aware of temporal and spatial heterogeneities in nutrient distribution and discuss this based on variabilities in the Ba/Ca records across specimen.

3.04. *"Finally, because of the discussion of ocean acidification is a major component of this manuscript, it also may be valuable for the authors to also include carbonate parameters for the area (i.e., omega-aragonite, TA, pH, etc.)."*

AR: We regret that except for data from the Arabian Sea Expedition (1995) recorded during the southwest monsoon (upwelling) and northeast monsoon (non-upwelling), no additional information on the carbonate chemistry of the northern Arabian Sea is available. Existing data from the Arabian Sea Expedition on seawater aragonite saturation (Ω_{sw}) are reported in the methods section of the discussion paper (lines 101-105) and are discussed in the following (line 370).

Minor edits:

Abstract

3.05. *"Lines 14-15: This statement is a bit of an overstatement. Calcification responses to changing environments is very well studied. If this is intended to be in terms of a specific type of environmental variation, then that needs to be clarified."*

AR: We have revised the sentence to read: "The calcification response of reef corals to rapid and simultaneous changes in Ω_{sw} and seawater nutrient concentrations is not well studied, however."

Introduction

3.06. *"Line 29: Consider replacing 'zooxanthellate' with symbiotic."*

AR: We have replaced the word "zooxanthellate" by "symbiotic".

3.07. *"Lines 36-37: This statement should be backed with the literature. Coral calcification is not highly debated; however, responses are highly variable. I recommend referencing several papers covering this here."*

AR: We have revised the sentence to read: "The responses of reef coral calcification on this rapidly changing environment are highly variable and remain currently a matter of debate." and covered this statement with literature from Cornwall et al., (2021), Guan et al., (2020) and Hall et al., (2018).

3.08. *"Lines 50-52: This statement seems misplaced and should be incorporated better within the introduction. Additionally, recent reviews suggest different calcification responses in corals under global change (see Cornwall et al 2021, Global declines in coral reef calcium carbonate production under ocean acidification and warming, PNAS)."*

AR: We have removed this sentence because variable responses in corals under global change are already addressed in the introduction where the reference to the work of Cornwall et al., (2021) is cited (see RC2-3.07).

3.09. *"Line 54: savage disposal? Do you mean sewage?"*

AR: We have revised the spelling mistake to "sewage".

3.10. *"Lines 54-55: This is an incomplete statement."*

AR: We have revised the sentence to read: "Eutrophication can have both beneficial as well as detrimental effects on coral growth, however (Tomascik and Sander, 1985; Tomascik, 1990)."

3.11. *"Lines 55-56: Again, I suggest updating your language here to reflect more recent terminology of coral algal symbionts (see LaJeunesse et al. 2018, Systematic Revision of Symbiodiniaceae Highlights the Antiquity and Diversity of Coral Endosymbionts, Current Biology)."*

AR: We have revised the sentence to read: “Reef corals are highly adapted to oligotrophic waters with micro-algae symbionts to allow an efficient use of essential nutrients and to outcompete other fast-growing biota on a reef whose growth is inhibited by the undersupply of nutrients (Barrot and Rohwer, 2012; LaJeunesse et al., 2018; Vermeij et al., 2010).”

3.12. *“Lines 66-68: These sentences could be a bit stronger to introduce this important topic in your introduction.”*

AR: We have revised the sentence to read: “Understanding how coral calcification responds to rapid changes in seawater nutrient conditions and Ω_{sw} is critical for more accurate predictions on the persistence of reef habitats under the influence of global change.”

3.13. *“Lines 70-72: This statement would benefit from a clear connection of how calcification responses from upwelling locations can be applied to systems without upwelling.”*

AR: We have revised the sentence to read: “This allows these regions to serve as natural laboratories to investigate the calcification response of reef corals to these multiple environmental stressors that are likely to affect global coral reefs in the near future (Camp et al., 2018; Wizemann et al., 2018).“

3.14. *“Lines 84-125: This section should be moved into the methods as a section describing the sites. A condensed version of this could be included in the previous paragraph to describe the sites if that is desired.”*

AR: We have moved the chapter "Arabian Sea climate and oceanography" to the beginning of the methodology section in the revised version of the manuscript.

Methods

3.15. *“Lines 128-134: It sounds like these colonies were not collected in situ, rather collected as dead skeletons from the beach. What about differences in local conditions? If these corals were washed up on shore you don’t really know what depth or location they came from? Also what years? How do you know when they washed up on the beach?”*

AR: This reviewer comment will be split into three sections, which will be answered separately in the following:

„*…when were they washed up on the beach*?“

AR: Certainly, all the corals were washed up on the beach by the same event, as they were all collected from the same storm deposit, which is attributed to Cyclone Gonu in 2007 (Fritz et al., 2010).

„*…also what years*?“

AR: The detailed information about the calendar years represented in our records is marginal, as we establish generalized annual calcification records with monthly resolution from several years of the total record lengths (Multi-year monthly means). These generalised records represent the mean monthly calcification of *Porites* corals at Masirah Island during the more recent current era.

„*…What about differences in local conditions…depth or location*?“

AR: In the revised version of our manuscript, we discuss intra-annual variability of calcification (in particular between the upwelling season and non-upwelling season) with regard to seasonal environmental changes. Location factors are hereby to be neglected, as they remain uniform within a single specimen.

3.16. *“Lines 216-219: Unclear what these numbers and acronyms represent. Please rephrase in a clearer way.”*

AR: These acronyms refer to the two monsoon seasons (SWM = Southwest Monsoon, NEM = Northeast Monsoon) and the intermonsoon seasons (SIM = Spring Intermonsoon, AIM = Autumn Intermonsoon), respectively, and are introduced in the preceding chapter "Arabian Sea climate and oceanography" (lines 88-92) of the discussion paper. However, to ensure better reading in the section "Data matching and age model development" (lines 216-216), we have revised the section to read:

"A detailed chronological frame for the Li/Mg records was established with the aid of the generalized annual record of remote sensing SST data (JPL MUR, daily averaged 2003 – 2018) (Fig. 2). This data demonstrates average calendar dates of seasonal extremes to occur on 31 May during spring intermonsoon (SIM), on 15 August during southwest monsoon (SWM), on 25 October during autumn intermonsoon (AIM) and on 06 February during northeast monsoon (NEM). Average dates of inflection points between consecutive seasons from the generalized annual SST record are 18 March (NEM – SIM), 25 June (SIM – SWM), 30 September (SWM – AIM) and 10 December (AIM – NEM)."

3.17. *"Note on the standard corals: How do we know that the other corals are effective standards for comparison? Who is to say that they were not influenced by SST or OA? Or other factors?"*

AR: We do not exclude the influence of environmental factors other than SST on the calcification of the standard corals (GBR and Hawaii) at any point. Based on the highly convincing correlations with SST (bulk density: $r^2 = 0.49$, $p < 0.0001$; extension rate: $r^2 = 0.9$, $p < 0.0001$), we stated that calcification of these corals is "<u>largely</u> controlled" by water temperature (Lough and Barnes, 2000).

Results

3.18. *"Lines 248-249: Do these n refer to the number of transects for the measures?"*

AR: These n refer to the number of years that were used to calculate the mean annual bulk density of the individual coral samples.

Discussion

3.19. *"A lot of the current discussion is results. These should be moved to the results section and then the discussion can include more incorporation of implications/meaning of these results."*

AR: Thank you very much for this advice. We have moved several parts of the discussion (e.g., an updated version of Figure 9) to the results.

3.20. *"Lines 285-288: But don't you expect biological variability?"*

AR: This quantitative comparison of our data with data of *Porites* from the Indo-Pacific no longer appears in the revised version of our manuscript (see RC2-3.02).

3.21. *"Lines 367-369: Split into two different sentences for easier reading."*

AR: We have revised the section to read: "This finding implies that there is no intensified upregulation of internal Ω_{cf} relative to Ω_{sw} during the non-upwelling seasons (McCulloch et al., 2017; DeCarlo et al., 2018; D'Olivo and McCulloch, 2017). As an explanation, we propose that internal upregulation processes of corals affected by seasonal upwelling are not capable to adapt completely to ocean chemistry change on a quarterly scale. As a consequence, a relatively low Ω_{cf} is maintained year-round so as to avoid high gradients to the external Ω_{sw} during southwest monsoonal upwelling."

3.22. *"Lines 414-433: This section is lacking incorporation of the current literature and needs some more grounding in terms of what is known and previous work."*

AR: The implication of our results described in this section largely refers to the enhanced annular mean extension rates and the lower skeletal density observed in *Porites* from Masirah Island compared to the reference data from the Indo-Pacific (Lough and Barnes, 2000). Given the reframing of the discussion part, this section will undergo a major reorganisation. The revised focus will then be on the implications derived from the comparison of intra-annual patterns of calcification (upwelling season vs. non-upwelling season) (see chapter 4.3. of the discussion paper: "Monthly records of coral calcification"). A revised key aspect will be the finding of a constant and year-round relatively low skeletal density regardless of the mere 3-month time span of upwelling (disscussed in lines 364-376 in the discussion paper).

Figures

3.23. *"Figure 1: This is a really helpful figure to demonstrate this reef system, collection site, and the currents/upwelling, however, this figure could be made a bit clearer with a few updates as suggested here. There is a lot going on with colours so I recommend making your land either white or grey to make the focus of the map more on the reef locations. I also recommend selecting a different colour to represent the coral reef provinces with better contrast against the red and blue."*

AR: We have turned the colour of the land surface greyish to put more focus on the reef locations. The yellow colour of the coral reef provinces contrasts most strongly with the adjacent red and blue colours, which is why we consider it to be exceptionally suitable.

3.24. *"Figure 2/3: Please define NEM, SIM, SWM, and AIM in your figure captions."*

AR: We have defined the abbreviations in the figure captions.

3.25. *"Figure 3: please include what years were assessed in to calculate these monthly values."*

AR: We have included the number of years used for the calculation of the multi-year monthly means.

3.26. *"Figure 5: again, please include the years assessed in the monthly values."*

AR: We have included the number of years used for the calculation of the multi-year monthly means.

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