Geochemistry Geophysics Geosystems G3

Reply
Volume 12, Number 3
30 March 2011
Q03013, doi:10.1029/2010GC003461
ISSN: 1525-2027

Published by AGU and the Geochemical Society

Reply to comment by Cahyarini et al. on "A snapshot of climate variability at Tahiti at 9.5 ka using a fossil coral from IODP Expedition 310"

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Components: 3700 words.

Keywords: Sr/Ca; oxygen isotopes; early Holocene.

Index Terms: 4916 Paleoceanography: Corals (4220); 4922 Paleoceanography: El Nino (4522); 4954 Paleoceanography: Sea surface temperature.

Received 3 December 2010; **Revised** 31 January 2011; **Accepted** 9 February 2011; **Published** 30 March 2011.

DeLong, K. L., T. M. Quinn, C.-C. Shen, and K. Lin (2011), Reply to comment by Cahyarini et al. on "A snapshot of climate variability at Tahiti at 9.5 ka using a fossil coral from IODP Expedition 310," *Geochem. Geophys. Geosyst.*, *12*, Q03013, doi:10.1029/2010GC003461.

[1] *Cahyarini et al.* [2011] take exception to the methods used and the results reported in our recent paper [*DeLong et al.*, 2010a]. The traditional approach to estimating sea surface temperature (SST) from variations in coral skeletal geochemistry involves calibrating measurements of SST from the coral's location with the observed geochemical variations (e.g., Sr/Ca and δ^{18}O). Individual proxy calibrations at individual reef locations are not the same, but generally converge to community-accepted values and associated uncertainties [e.g., *Corrège*, 2006]. SST estimates based on geochemical variations in fossil corals present even larger challenges because additional factors (e.g., changes in seawater chemistry, postdepositional alteration, and reef geomorphology) must be accounted for in the SST reconstruction. We (i.e., T. M. Quinn, his students, and associates) understand and respect these challenges, which we included in our research strategy.

[2] *Cahyarini et al.* [2011] note that large discrepancies can occur in coral Sr/Ca; we do not dispute this fact and we discuss in detail the sources of differences in the *DeLong et al.* [2010a] study. We note that many of the differences can be controlled for by (1) careful selection of coral colonies to be

sampled for calibration studies, (2) following consistent sampling procedures, and (3) constraining environmental factors. Comparisons of mean coral Sr/Ca should be made with the same parameters to eliminate known effects due to species differences, sampling effects, and environmental settings (e.g., water depth and lagoon versus open ocean). These differences are problematic for fossil coral studies where water depth and environmental setting are difficult to constrain and we discuss in detail the possible implications for reconstructing temperature from coral geochemistry in the *DeLong et al.* [2010a] study.

[3] Indeed, we have explicitly investigated the source of variability in coral Sr/Ca and δ^{18}O over the years at several reef sites and with multiple coral genera [*Stephans et al.*, 2004; *Smith et al.*, 2006; *DeLong et al.*, 2007, 2009]. We have also published papers noting the deficiencies in the coral Sr/Ca-SST proxy [*Quinn and Taylor*, 2006; *Smith et al.*, 2006; *Kilbourne et al.*, 2008]. These and other studies [*Leder et al.*, 1996; *Alibert and McCulloch*, 1997; *Cohen and Hart*, 1997; *Marshall and McCulloch*, 2002; *Swart et al.*, 2002; *Cohen et al.*, 2004; *Giry et al.*, 2010] have confirmed that proper physical sampling of the coral skeleton is critical in terms of producing robust, reproducible coral Sr/Ca and δ^{18}O time series.

[4] We evaluated the work on modern corals from Tahiti because it is the logical starting point for our paper on fossil corals from Tahiti. When we wrote the Tahiti fossil coral paper, there was one modern study with data publicly available for interpretation of the fossil coral data [*Boiseau et al.*, 1998] and two studies by *Cahyarini et al.* [2008, 2009] for which data was requested and denied. In a subsequent request, Cahyarini agreed to provide monthly coral Sr/Ca summaries only (S. Y. Cahyarini, personal communication, 2009). Therefore, we used the available data from *Boiseau et al.* [1998] to compare the possible range of coral δ^{18}O variability with the nine year long fossil coral record [*DeLong et al.*, 2010a, Figure 4]. We preferred to do the same with the coral δ^{18}O and Sr/Ca data from *Cahyarini* [2006] and *Cahyarini et al.* [2008, 2009], but that was not possible, as the data from those studies was not made available for the interpretation of the fossil coral record. Instead, we used a range of coral Sr/Ca slopes from similar studies of *Porites* in the South Pacific and a mean annual calibration based on South Pacific *Porites* from the same laboratory. We decided we could not make a reliable determination seawater δ^{18}O (δ^{18}Osw) due to the lack of data access and uncertainties in the modern Tahiti calibration study by *Cahyarini et al.* [2009] as we discuss in the *DeLong et al.* [2010a] study. Therefore, the *Cahyarini et al.* [2008] study was not discussed or referenced in the study by *DeLong et al.* [2010a]. In regards to the comment by *Cahyarini et al.* [2011, paragraph 2] that states "The magnitude of expected δ^{18}Osw variations is smaller than the analytical error of δ^{18}O and Sr/Ca," *Boiseau et al.* [1998] measured δ^{18}Osw seven times in their study at nearby Moorea [see *DeLong et al.*, 2010a, Figure 1] from March 1995 to April 1996 and found ~0.45‰ seasonal variability, which is an order of magnitude greater than δ^{18}O analytical precision. The comment by *Cahyarini et al.* [2011, paragraph 2] states, "…modern δ^{18}Osw variations at Tahiti are too small to measurably affect coral δ^{18}Osw." This is clearly incorrect when actual δ^{18}Osw data are examined.

[5] Our evaluation of the Tahiti fossil coral record for interannual and seasonal variability considered a range of coral Sr/Ca and δ^{18}O slopes for *Porites* spp., including those of *Cahyarini et al.* [2009]. The range of coral Sr/Ca slopes (–0.05 to –0.075 mmol/mol/°C) we used includes slope values (–0.05 mmol/mol/°C) presented by *Cahyarini et al.* [2009] for corals TH1 and TH1B. Had we included the slope for TH2 (–0.04 mmol/mol/°C) from *Cahyarini et al.* [2009], the interannual and seasonal differences between coral δ^{18}O and Sr/Ca would have been even larger than those presented in the *DeLong et al.* [2010a] study. The larger seasonal cycle in SST is inconsistent with model results for the early Holocene [*Kutzbach et al.*, 1998] that reveals little change in tropical Pacific SST seasonality.

[6] *Cahyarini et al.* [2011, paragraph 2] wrote that we "…***speculate*** that a δ^{18}O-SST relationship of −0.18 (±0.04) per mil/°C could indicate contributions of δ^{18}O seawater, as inorganic aragonite has a δ^{18}O-SST relationship of −0.22 per mil/°C." This statement is not correct. A slope of –0.2‰/°C for δ^{18}O was ***assumed*** by *DeLong et al.* [2010a, Figure 5] for the seasonal and interannual temperature comparison. The value is close to the slopes of –0.17 to –0.19‰/°C for *Porites* that was carefully established during drought years [*Gagan et al.*, 1998] and with in situ monthly seawater δ^{18}O data [*Shen et al.*, 2005]. In addition, varying the δ^{18}O slope from –0.18 to –0.22 ‰/°C does not change the results of our study; the seasonal variability difference between coral δ^{18}O and Sr/Ca is approximately the same or greater. The interannual anomalies reveal a shift to cold/wet and warm/dry regardless of δ^{18}O slopes (–0.18 to –0.22 ‰/°C) used and we did not quantify the difference or the δ^{18}O of seawater

due to the uncertainties with the modern calibration studies.

[7] We chose to develop and apply a regional south Pacific Sr/Ca to SST and $\delta^{18}O$ to SST calibration based on the mean values of each variable. The mean calibrations presented by *DeLong et al.* [2010a] were (1) selected from studies of the same coral genus *Porites*, (2) analyzed in the same laboratory following the same analytical procedures with the same laboratory standards, (3) microsampled following the method outlined by *Quinn et al.* [1996], (4) carefully selected and completely submerged coral colonies located in areas exposed to open ocean conditions for paleoclimate reconstructions, and (5) not sampled along suboptimal mesoscale growth structures. Our thought was not to produce a "universal" set of equations, but rather we hoped to produce a quantitative relationship between *Porites spp*. geochemistry and temperature that could be used over a range of temperatures and environmental conditions likely to have been observed in the south Pacific over the last 20 ka. *Cahyarini et al.* [2011] choose to create a figure depicting mean Sr/Ca determinations for two different coral genera (*Porites* and *Diploria*), one from the Indian and Pacific Oceans and the other from the Atlantic Ocean, from 7 published and 11 non-published data sets. Species effects between different coral genera for coral Sr/Ca have been documented with ranges up to 0.231 mmol/mol [*Harriss and Almy*, 1964; *Livingston and Thompson*, 1971; *Weber*, 1973; *Oomori et al.*, 1982; *Cross and Cross*, 1983; *de Villiers et al.*, 1994; *DeLong et al.*, 2009]. If we compare coral Sr/Ca from *Porites* and *Diploria strigosa* [*Dunn et al.*, 2008; *DeLong et al.*, 2009] from locations with similar mean temperature that were measured by the same analytical procedures with the same standards, we find mean differences up to 0.294 mmol/mol. We note that a recent studies with *D. strigosa* examined different sampling methods (varying drill bit size) along the theca, septa, and columella of this species found significant sampling heterogeneities that shifted mean coral Sr/Ca by 0.062 to 0.266 mmol/mol [*Giry et al.*, 2010]. A similar comparison with the Atlantic species *Montastraea faveolata* with *Porites* reveals a mean difference of 0.208 mmol/mol [*Kilbourne et al.*, 2004, 2008]. These data demonstrate that species effects are apparent in coral Sr/Ca thus including different coral genera in a calibration is inappropriate.

[8] We estimated a mean SST of 24.3°C ± 0.3°C for the 9.5 ka Tahiti coral using the regional *Porites* Sr/Ca to SST relationship. We note that the ±0.3°C uncertainty is only the error of regression hence, is a minimal estimate of uncertainty. We devoted a section of the discussion to the possible sources of uncertainties and state in our conclusions [*DeLong et al.*, 2010a, paragraph 25] "We recognized a large uncertainty in coral Sr/Ca is related to or the combined effects of differences observed between corals from the same region, various water depths, local environmental conditions, and possible undetected diagenetic alteration."

[9] *Cahyarini et al.* [2011] note a few recently published papers that bear on climate reconstructions using fossil corals. We note that the *Abram et al.* [2009] paper was in the review process simultaneously with *DeLong et al.* [2010a], but that paper was published a few months prior to our paper. *Abram et al.* [2009] analyzed a suite of modern and fossil corals from the Indo-Pacific warm pool for Sr/Ca using a variety of sampling resolutions (monthly, yearly, and bulk). Six modern corals at Mentawai Islands have a range of record lengths, sampling resolution, and mean Sr/Ca values; the minimum mean Sr/Ca is observed in a record that spans 1982 to 1993 with yearly sampling and the maximum mean Sr/Ca is observed in a record that spans 1993 to 1997.2 with monthly sampling. Variations in sampling resolution can produce mean shifts in coral geochemistry [*Leder et al.*, 1996; *Quinn et al.*, 1996; *DeLong et al.*, 2007]. Additionally, no information is given regarding water depth or environment in the study by *Abram et al.* [2009, Table 1]. The Muschu/Koil Island site in the study by *Abram et al.* [2009] has a smaller mean difference (0.05 mmol/mol) between the corals sampled with the same resolution over the same time interval. The fossil coral study completed by *Abram et al.* [2009] is rare in that it uses multiple fossil coral samples, many of which overlap in age, to reach their conclusions. Such an opportunity was not available for our work at Tahiti.

[10] Regarding the *Inoue et al.* [2007] experimental results, the largest variability in coral Sr/Ca was observed at the temperature extremes of the experiment in which the corals were subjected to a constant temperature for 142 days. The corals in the *Inoue et al.* [2007] study with the largest variability in mean Sr/Ca (~0.4 mmol/mol) were those exposed to the extreme temperatures (21°C and 29°C) for a prolonged period. These prolonged thermal conditions may have stress the corals and it has been suggested that stress may be reflected in coral geochemistry [*Marshall and McCulloch*, 2002; *Fallon et al.*, 2003; *Mitsuguchi et al.*, 2008].

[11] Last, we would like to take this opportunity to compare the results from *DeLong et al.* [2010a] with another IODP Expedition 310 study that was published while our paper was in press. *Inoue et al.* [2010] examined coral Mg/Ca and U/Ca as a proxy for SST and Ba/Ca and Cd as an upwelling proxy. *Inoue et al.* [2010] found a mean SST of ~22°C for the 9.8 ka, which is ~2°C colder than that reported by *DeLong et al.* [2010a] for 9.5 ka. Additionally, *Inoue et al.* [2010] found that the colder temperatures between 12.6 and 9.8 ka were associated with higher Ba/Ca and Cd levels suggesting upwelling and/or entrainment of subsurface water into the mixed layer was enhanced around Tahiti in the early Holocene. This evidence supports our colder temperature reconstruction and our hypothesis of localized upwelling for the early Holocene in Tahiti.

Acknowledgments

[12] The data from 310-M0007B-11R-2 is archived as Data Contribution Series # 2010–054 [*DeLong et al.*, 2010b].

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