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Supporting Information for

Ocean Acidification has Impacted Coral Growth on the Great Barrier Reef

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Text S1. Model simulations with the consideration of potential temperature effects on coral calcifying fluid pH and DIC

The *Porites* skeletal growth model we employed links the skeletal density with the external seawater environment via its influence on the chemistry of coral calcifying fluid (Mollica et al., 2018), especially the dependence of coral calcifying fluid pH on the external seawater pH (e.g., Trotter et al., 2011; McCulloch et al., 2012). Recent studies of natural *Porites* corals suggest temperature also affects the pH and dissolved inorganic carbon (DIC) concentration of coral calcifying fluid, via its control on the rates of carbonate precipitation in the calcifying fluid (Guo, 2019) or coral metabolism (e.g., McCulloch et al., 2017). Specifically, studies of 2 *Porites* colonies around the Great Barrier Reef show consistent decreases in their calcifying fluid pH but increases in calcifying fluid DIC with increasing seawater temperature, with sensitivities ranging from -0.011 to -0.024/°C and from 10.8% to 13.9%/°C, respectively (McCulloch et al., 2017).

Model simulations including these additional temperature effects were conducted, with assumed temperature sensitivities of -0.02/°C and 12%/°C respectively for calcifying fluid pH and DIC respectively (i.e., the average sensitivities observed in the above GBR *Porites* colonies; McCulloch et al., 2017). Results from these simulations show that the incorporation of these additional temperature effects into the skeletal growth model has negligible effects on our findings (Fig. S8).

Text S2. Recalculation of reef-water pH at the Great Barrier Reef

In order to remove the methodological inconsistency in reef-water pH estimations at the Great Barrier Reef among different studies (e.g., regarding the use of boron isotope fractionation factors; Pelejero et al., 2005; Wei et al., 2009; D'Olivio et al., 2015), we recalculated reef-water
pH values based on the boron isotope composition of coral skeleton reported in previous studies as follows (Trotter et al., 2011; D'Olivo et al., 2015):

\[
pH_{sw} = \frac{pH_{cf} - 5.954}{0.32}
\]

\[
pH_{cf} = pK_B - \log \left( \frac{\delta^{11}B_{coral} - \delta^{11}B_{sw}}{\delta^{11}B_{sw} - \alpha_B \times \delta^{11}B_{coral} - 1000 \times (\alpha_B - 1)} \right)
\]

where \( pH_{sw} \) and \( pH_{cf} \) denote the pH of seawater and the coral calcifying fluid, \( \delta^{11}B_{sw} \) and \( \delta^{11}B_{coral} \) represent the boron isotope composition of seawater and coral skeleton, respectively (\( \delta^{11}B_{sw} = 39.61\% \), Foster et al., 2010), \( \alpha_B = 1.0272 \) is the boron isotope fractionation between borate ion and boric acid (Klochko et al., 2006) and \( pK_B \) is the dissociation constant of boric acid (Dickson, 1990).

Note, incorporation of the potential temperature effects on \( pH_{cf} \) (e.g., McCulloch et al., 2017; Guo, 2019; see also Text S1) affects the absolute magnitudes of the estimated \( pH_{sw} \) but has negligible influence on the temporal trends of \( pH_{sw} \) at these GBR reef sites, because these sites do not show coherent temperature trends over the period of our pH-reconstruction (i.e., 1966 to 2000).

**Text S3. Notes on temporal trends in Porites skeletal growth on the Great Barrier Reef**

The temporal changes in Porites skeletal growth we determined for the Great Barrier Reef are similar to the trends derived previously based on a collection of both long and short Porites cores over 1900-2005 (De'ath et al., 2009; De'ath et al., 2013). However, our analysis suggests an insignificant change in coral calcification between 1990 and 2000 (Fig. 1), as a result of concurrent increase in skeletal extension but decrease in skeletal density. This contrasts against the 11.4% reef-wide decline in both skeletal extension and calcification between 1990
and 2005 suggested by De'ath et al. (2009) and De'ath et al. (2013). This difference arises mainly from the exclusion of short Porites cores in our analysis, which, as noted in previous re-analyses of this same dataset, reduces the potential ontogenetic effects and biases towards inshore reefs (D'Olivo et al., 2013; Ridd et al., 2013).

Text S4. Contribution of different factors to the changes in Porites skeletal growth at South China Sea (Hainan Island) and Central Pacific Ocean reefs

We partitioned the contributions of extension, temperature, and carbonate chemistry changes to the observed coral skeletal density declines at South China Sea (Hainan Island) and central Pacific reefs, following the same approach employed for the Great Barrier Reef corals (Equation 1, section 2). Our model predicts that skeletal extension acting alone would have caused ~16% and ~7% declines in Porites skeletal density at South China Sea (Hainan Island, over 1901-2000) and central Pacific reefs (over 1978-2004, Fig. S5), respectively. In comparison, variations in water temperature alone would have caused only modest oscillations of Porites skeletal density at these two regions, i.e., between ~2% and ~4% for South China Sea and between ~-5% and ~5% for central Pacific reefs (Fig. S5). Together, skeletal extension and ocean temperature changes are expected to lead to ~18% and ~12% declines in Porites skeletal density at these two regions, which in turn leads to an estimated ~7±3% (95% confidence interval) decline in Porites skeletal density induced by OA at South China Sea (Hainan Island) from 1901 to 2000 but insignificant OA-induced density changes on central Pacific reefs over 1978-2014 (Equation 1, Fig. S5).
Fig. S1. Locations of the reefs and age distributions of *Porites* cores included in our analysis. (a) Locations of the 39 GBR reefs (De'ath et al., 2009). (b) Locations of the 2 South China Sea (Hainan Island) reefs (Su et al., 2016). (c) Locations of the 7 central Pacific reefs (red circles, this study). For comparison, the locations of GBR (green circles) and the South China Sea reefs (yellow circles) are also shown in (c). (d-f) Number of contributing *Porites* colonies at each year over our selected time periods on the Great Barrier Reef, the South China Sea, and the central Pacific reefs. The size of each symbol in (a-b) and the numbers in (c) denote the number of cores at the corresponding reef. The white dashed lines in (a) denote latitude 9°S, 17°S and 20°S, based on which we further separated the GBR cores into Northern GBR, Central GBR and Southern GBR in some of our analyses in order to investigate potential variations in skeletal growth among different parts of the Great Barrier Reef (Fig. S6-S7).
Fig. S2. Annual anomalies in *Porites* skeletal parameters at three regions: (a-c), Great Barrier Reef; (d-f) South China Sea (Hainan Island); (g-i) Central Pacific Ocean. All anomalies are calculated relative to the corresponding mean values over 1951-1960 (for Great Barrier Reef, South China Sea) and 1998-2007 (for Central Pacific Ocean), respectively, the common periods that all cores from the corresponding regions cover (Methods).
Fig. S3. Number of reef-water pH records available at each year on the Great Barrier Reef over our selected time period (1871-2000) and the estimated reef water pH anomalies. Reef-water pH values were estimated based on the boron isotope composition of *Porites* skeletal cores (Pelejero et al., 2005; Wei et al., 2009; D'Olivo et al., 2015; Text S2, section 2). To robustly investigate the multi-decadal variations in reef-water pH, we limit our analysis to the time period when at least 5 pH records are available for each year, i.e., from 1966 to 2000 (section 2). For each record, the pH anomalies are calculated relative to its corresponding mean values over 1976-1985, a common period that all these selected pH records cover.
Fig. S4. Partial-effects plots showing changes in *Porites* skeletal parameters over time at three regions: (a-c), Great Barrier Reef; (d-f) South China Sea (Hainan Island); (g-i) Central Pacific Ocean. The gray bands indicate 95% confidence intervals for the predicted value for any given year.
Fig. S5. Contributions of different factors (i.e., extension, temperature, OA) to the changes in *Porites* skeletal density at three regions: (a-c) Great Barrier Reef; (d-f) South China Sea (Hainan Island); (g-i) Central Pacific Ocean. The impact of ocean acidification (OA) is determined by subtracting the model predicted effects of extension and temperature (dashed line, panels c, f, i) from the measured density (Equation 1). Also shown for comparison are the temporal changes in each factor (upper panels) and the experimentally measured bulk changes in *Porites* skeletal density (black line, lower panels).
Fig. S6. Partial-effects plots showing changes in *Porites* skeletal parameters over time at different sections of the Great Barrier Reef. Northern, central and southern GBR refer to reef sites north of 17°S, between 17°S and 20°S, and south of 20°S, respectively (Fig. S1). ‘n’ denotes the number of *Porites* cores in each section. The gray bands indicate 95% confidence intervals for the predicted value for any given year.
Fig. S7. Impacts of OA on *Porites* skeletal density at different sections of the Great Barrier Reef. Northern, central and southern GBR refer to reef sites north 17°S, between 17°S and 20°S, and south of 20°S, respectively (Fig. S1). The OA-induced decline in *Porites* skeletal density is consistently born out in all three parts of the GBR, despite the differences in their bulk density records (Fig. S6). For comparison, the estimated impact of OA over the whole Great Barrier Reef is also shown (black line and gray band).
Fig. S8. Comparison of OA-induced *Porites* skeletal density change estimated with and without (default) the consideration of potential temperature effects on coral calcifying fluid pH and DIC (Text S1, section 2, McCulloch et al., 2017; Guo, 2019): (a) Great Barrier Reef (GBR), (b) South China Sea (SCS) and Central Pacific Ocean (CPO) reefs.
**Table S1. Parameters of the *Porites* skeletal growth model.**

| Parameter                                      | Symbol | Value          | Reference                      |
|------------------------------------------------|--------|----------------|--------------------------------|
| Initial thickness of new skeletal element      | $\omega_0$ | 59.5 $\mu$m    | (Mollica et al., 2018)         |
| Decline of thickening rate with depth in the tissue | $\lambda$ | 12.8           | (Mollica et al., 2018)         |
| DIC elevation in coral calcifying fluid        | $\alpha$ | 2.05           | (Mollica et al., 2018)         |
| Calyx size                                     | $r_0$  | 0.63 mm        | (Mollica et al., 2018)         |
| Tissue thickness                               | $T_d$  | 5.30 mm (GBR, CPO) | (Lough and Barnes, 2000)   |
|                                                |        | 0.45-1.15 mm (SCS) | (Su et al., 2016)            |

**Data S1. Annual anomalies of *Porites* skeletal growth parameters at Great Barrier Reef, South China Sea, central Pacific reefs (relative to the corresponding means of the common periods) included in our analysis (separate file).**

**Data S2. Measured skeletal growth parameters of *Porites* cores from the central Pacific reefs (separate file).**

**Data S3. Anomalies of reef-water pH at Great Barrier Reef (relative to the corresponding mean over 1976-1985) included in our analysis (separate file).**
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