Diverse Coral Communities in Naturally Acidified Waters of a Western Pacific Reef

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Supporting Information

Sites

In September 2011 and March-April 2012 we collected 228 water samples at 9 different sites throughout the Palauan archipelago for TA and DIC analyses in order to characterize the spatial and temporal variability of the seawater CO_2 system within Palau. Samples were collected on the ocean side (sites 2 in Figure 1) and lagoon edge (sites 5 in Figure 1) of the northwestern barrier reef at Ngaremlengui; on the ocean side (site 1 in Figure 1) and lagoon edge (sites 3 and 4 in Figure 1) of the southeastern barrier reef at Uchelbeluu; in the northwestern lagoon (two unnumbered sites in Figure 1); at the edge of a southeastern fringing reef at Airai (site 6 in Figure 1); and within Risong Bay (sites 7 and 8 in Figure 1) and Nikko Bay (site 9 in Figure 1) in the Rock Islands.

Distance from offshore waters was determined using the ruler tool in Google Earth. For exposed sites (sites 3-6), a straight line perpendicular to the nearest barrier reef was measured from the site to approximately 300 m ocean ward of the barrier reef crest where breaking waves can be seen in the satellite image. For Rock Island sites (sites 7-9), the shortest path between islands from the site to approximately 300 m ocean ward of the nearest barrier reef crest was measured. The same offshore point was used for all three Rock Island sites.

Data Collection and Analyses

In situ temperature was measured in 2011 with TidbiT v2 water temperature data loggers produced by Onset with a manufacturer stated accuracy of 0.2 °C and in 2012 with a RBR XR-620 CTD with a manufacturer stated temperature accuracy of ±0.002 °C. Surface water (0-3 m) samples were collected multiple times a day between sunrise and sunset and on 3-9 separate days for each site from a Niskin bottle into 300 ml glass bottles (TA/DIC) and 125 ml glass bottles (salinity). Approximately 5 ml were removed from each bottle to allow headspace for expansion and each TA/DIC sample was poisoned with 50 µl saturated mercuric chloride solution immediately after collection to inhibit biological activity and then sealed with screw tops and tape. TA and DIC analyses were performed with a Versatile INstrument for the Determination of Total inorganic carbon and titration Alkalinity (VINDTA) produced by Marianda Marine Analytics and Data. The VINDTA uses coulometric titration for DIC analysis and an open cell potentiometric titration for TA analysis. DIC and TA measurements were standardized with certified reference materials obtained from Andrew Dickson at Scripps Institution of Oceanography [*Dickson*, 2001; *Dickson et al.*, 2007]. Analyses of replicate samples yielded a mean precision of ~2 µmol kg^{-1} and ~1 µmol kg^{-1} for DIC and TA analyses, respectively (n = 9 pairs).

Ecological data were provided by the Palau International Coral Reef Center (PICRC). At each site where teams of PICRC divers collected ecological data, five 50 m transects (the same transect length was used in *Fabricius et al.* [2011]) were laid on the reef at 3 and 10 m depth. For each transect, a photograph was taken at every meter, resulting in 50 photographs per transect. PICRC analyzes their coral ecological data to the genus level. To estimate coral cover, coral richness (number of coral genera), and coral diversity (Shannon diversity index), the photographs were analyzed using Coral Point Count with Excel extensions (CPCe) [*Kholer and Gill*, 2006]. Five random points from each quadrat were used to determine coral cover. Data from the 50 quadrats were averaged to provide the mean for each transect and the five transects were averaged to provide the mean for each depth at each site. Genus richness and diversity data were extracted from the transects and averaged for the depth at each site. Note that richness can be more useful for comparisons across regions than the Shannon diversity index which is sensitive to differences in evenness.

Calculations

The full seawater CO_2 system was calculated using salinity, temperature, TA, and DIC data using an Excel Workbook Visual Basic for Applications translation of the original CO2SYS program [*Lewis and Wallace*, 1998] by Pelletier, Lewis, and Wallace at the Washington State Department of Ecology, Olympia, WA. The CO2SYS program was run with carbonate constants from *Mehrbach et al.* [1973] refit by Dickson and Millero [1987].

Calculations were performed to determine the relative contributions of dilution, calcification, and respiration to decreased Ω_{ar} at our sites compared to offshore levels (Supplementary Figure S2). Ω is defined as the product of the concentration of calcium ions ($[Ca^{2+}]$) and CO_3^{2-} divided by the stoichiometric solubility product for the form of $CaCO_3$ (such as aragonite, which corals produce) being investigated (K^*_{sp}): $\Omega = [Ca^{2+}][CO_3^{2-}]/K^*_{sp}$. A decrease (increase) in $[CO_3^{2-}]$, therefore, results in a decrease (increase) in Ω. Dilution relationships between TA and salinity and between DIC and salinity were developed by mixing water with the average TA, DIC, temperature, and salinity of our offshore sites (averages of site 1 and 2 data, Supplementary Table S1) with fresh water. The TA of the fresh water end member was calculated with the S-TA relationship of *Lee et al.* [2006] for the tropical Pacific open ocean, the average temperature of our Palau sites, and salinity = 0. The DIC of the fresh water end member was calculated from the estimated TA at salinity = 0 assuming a 9:1 ratio of bicarbonate to carbonate ion concentration and that TA is well approximated by carbonate alkalinity (i.e. only carbonate and bicarbonate ions contribute to TA). To bound our estimates, calculations were also performed with dilution relationships using TA and DIC equal to zero for the fresh water end member. Both sets of calculations produced similar results with dilution accounting for 1 – 21 % and 2 – 30 % of the difference in Ω_{ar} between offshore and reef waters, using the S-TA relationship of *Lee et al.* [2006] and zero TA and DIC for the freshwater end members, respectively.

To quantify the contribution of calcification to decreased Ω_{ar} at our sites compared to offshore levels, it was assumed that dilution, calcification, and dissolution of $CaCO_3$ are the only processes that affect TA within the Palauan archipelago. Therefore, the differences between average offshore TA and the average TA measured at each site represent decreases in TA due to dilution and calcification combined ($TA_{meas} = TA_{dilut+cal}$). The DIC change due to dilution plus calcification ($DIC_{dilut+cal}$) was calculated from the average measured TA for each site using the dilution relationship described above and assuming a 2:1 decrease in TA:DIC for every mole of $CaCO_3$ produced. The green squares in Supplementary Figure S2 show Ω_{ar} at each site calculated from $TA_{dilut+cal}$, $DIC_{dilut+cal}$, and average *in situ* temperature and salinity. The difference between the Ω_{ar} due to dilution and calcification combined (green squares in Supplementary Figure S2) and the Ω_{ar} due to dilution alone (light blue dashed line in Supplementary Figure S2) gives the contribution of calcification to lowered Ω_{ar} at each of our sites (see green arrow in Supplementary Figure S2). Our calculations show that calcification accounts for 68 – 99 % and 64 – 98 % of the difference in Ω_{ar} between offshore and reef waters, using the S-TA relationship of ref. 19 and zero TA and DIC for the freshwater end members, respectively. However, most of our sites require another process to bring Ω_{ar} to the observed levels (dark blue arrows in Supplementary Figure S2); photosynthesis-respiration and groundwater discharge are likely candidates; the available data do not enable us to distinguish between the two. Our calculations show the barrier reef and exposed sites (sites 3-6) as net photosynthesizing and the Rock Island sites (sites 7-9) as net respiring (Supplementary Figure S2). However, changes in DIC due to net photosynthesis on the barrier reef and exposed sites are insignificant compared to changes due to calcification. This is shown in Figure 3 where the salinity corrected DIC-TA data fall within the error of the calcification relationship. However, in the Rock Islands, changes in DIC due to respiration and/or high CO_2 groundwater discharge are significant and account for 17 – 30 % and 18 – 32 % of the difference in Ω_{ar} between offshore and reef waters using the S-TA relationship of ref. 19 and zero TA and DIC for the freshwater end members, respectively. The influence of net respiration and/or groundwater input in the Rock Island bays is evident in Figure 3 which shows that the salinity corrected data fall to the right of the modeled calcification line.

Modern calcification rates of *Porites* corals at sites 4 and 9 were determined by averaging 2007-2009 rates. 2010 and 2011 calcification rates were excluded from average modern rates so they would not reflect the influence of a bleaching event that occurred throughout the Palauan archipelago in 2010. A full description of spatial and temporal variability in coral calcification will be published elsewhere.

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Figures

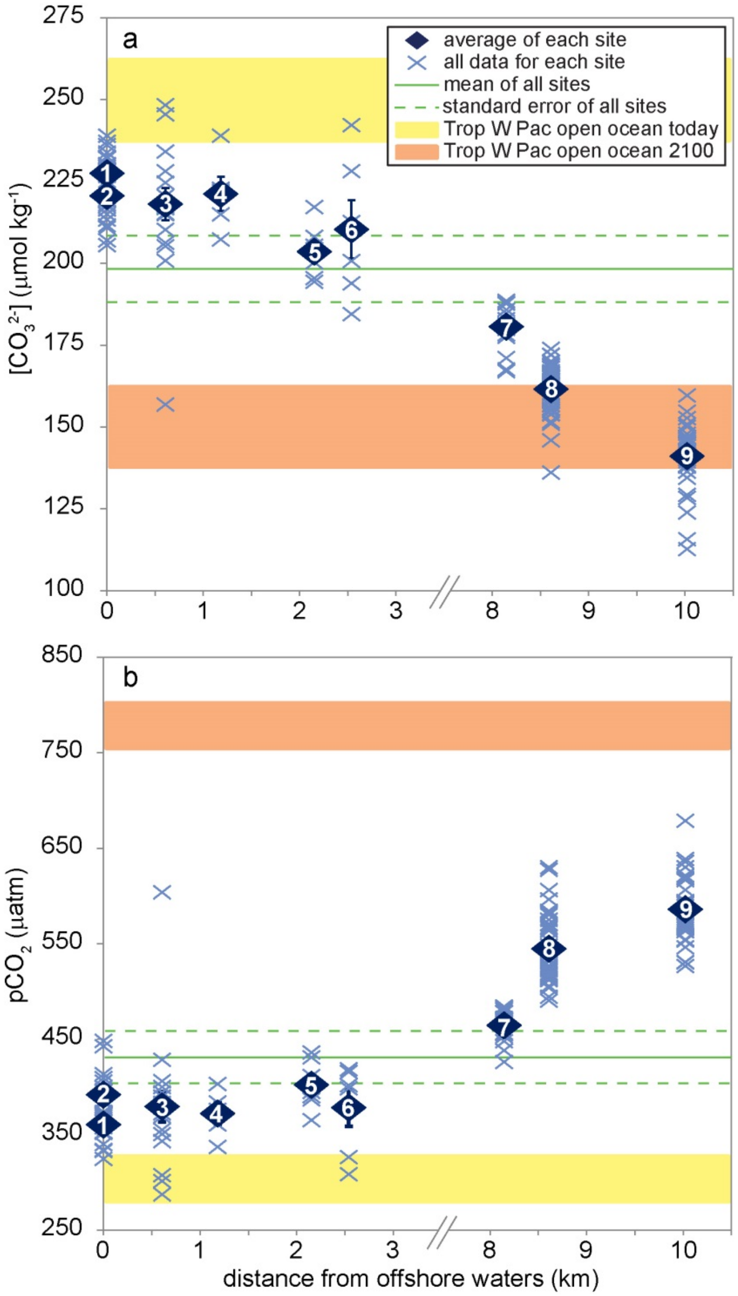

Figure S1. Average carbonate ion concentration $[CO_3^{2-}]$ (a) and pCO_2 (b) ± 1 standard error (dark blue diamonds with error bars) and all data collected (blue crosses) for each site versus distance from offshore waters. Shading represents the range of $[CO_3^{2-}]$ [*Feely et al.*, 2009] (a) and pCO_2 [*Steinacher et al.*, 2009] (b) in the tropical western Pacific open ocean in 2000 (yellow shading) and predicted for 2100 under the IPCC SRES A2 emissions scenario (orange shading). Green horizontal lines represent the mean (solid line) $[CO_3^{2-}]$ (a) and pCO_2 (b) of all sites ± 1 standard error of all sites (dashed green lines). Numbers on the symbols correspond to the site locations shown in Figure 1.

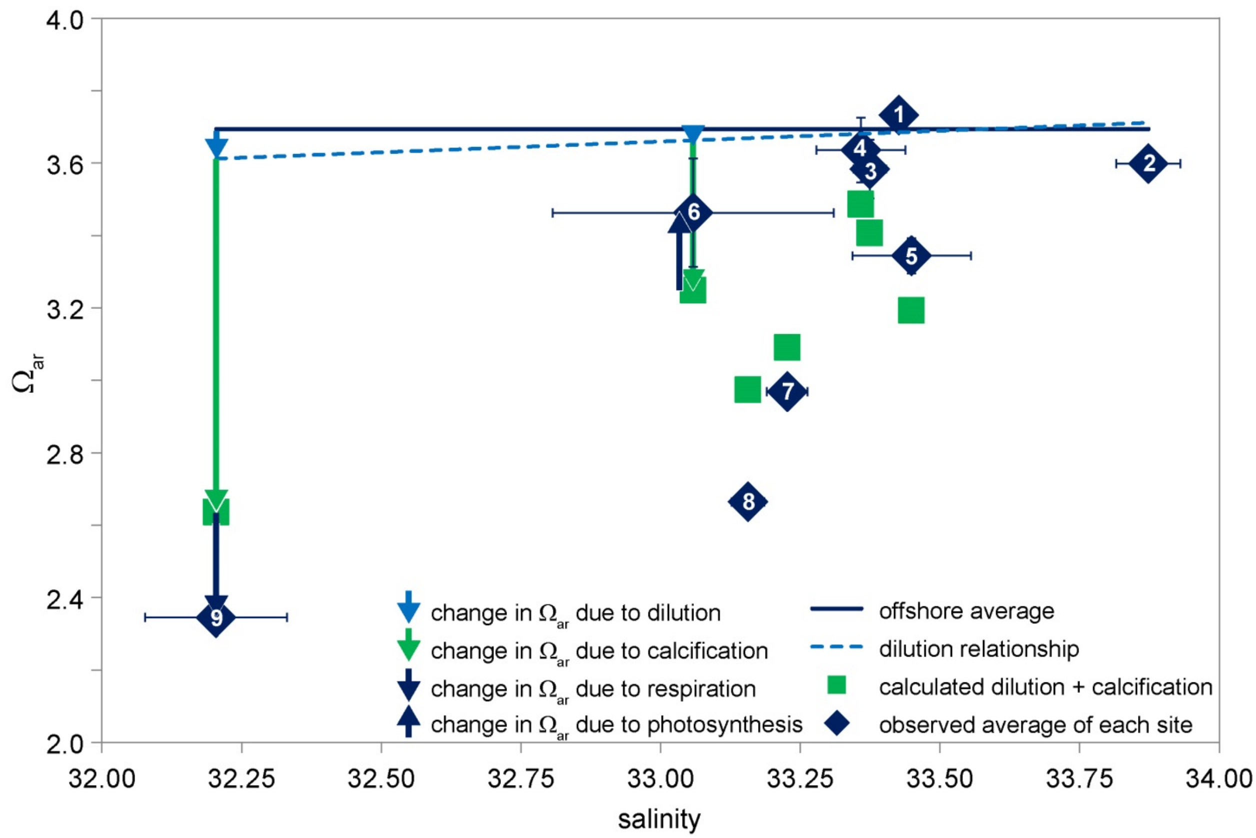

Figure S2. Average Ω_{ar} versus average salinity ± 1 standard error (dark blue diamonds with error bars). The solid dark blue horizontal line represents average offshore Ω_{ar}. The blue dashed dilution line represents the relationship between Ω_{ar} and salinity when average offshore water (average of site 1 and site 2 data) mixes with low salinity water. Green squares represent average Ω_{ar} calculated for each site if dilution and calcification were the only processes affecting Ω_{ar}. Numbers on the diamonds correspond to the site locations shown in Figure 1. The light blue arrows illustrate the change in Ω_{ar} from offshore levels due to dilution alone, using sites 6 and 9 as examples. The green arrows illustrate the change in Ω_{ar} due to calcification alone and the dark blue arrows illustrate the change in Ω_{ar} due to photosynthesis-respiration and/or groundwater discharge alone.

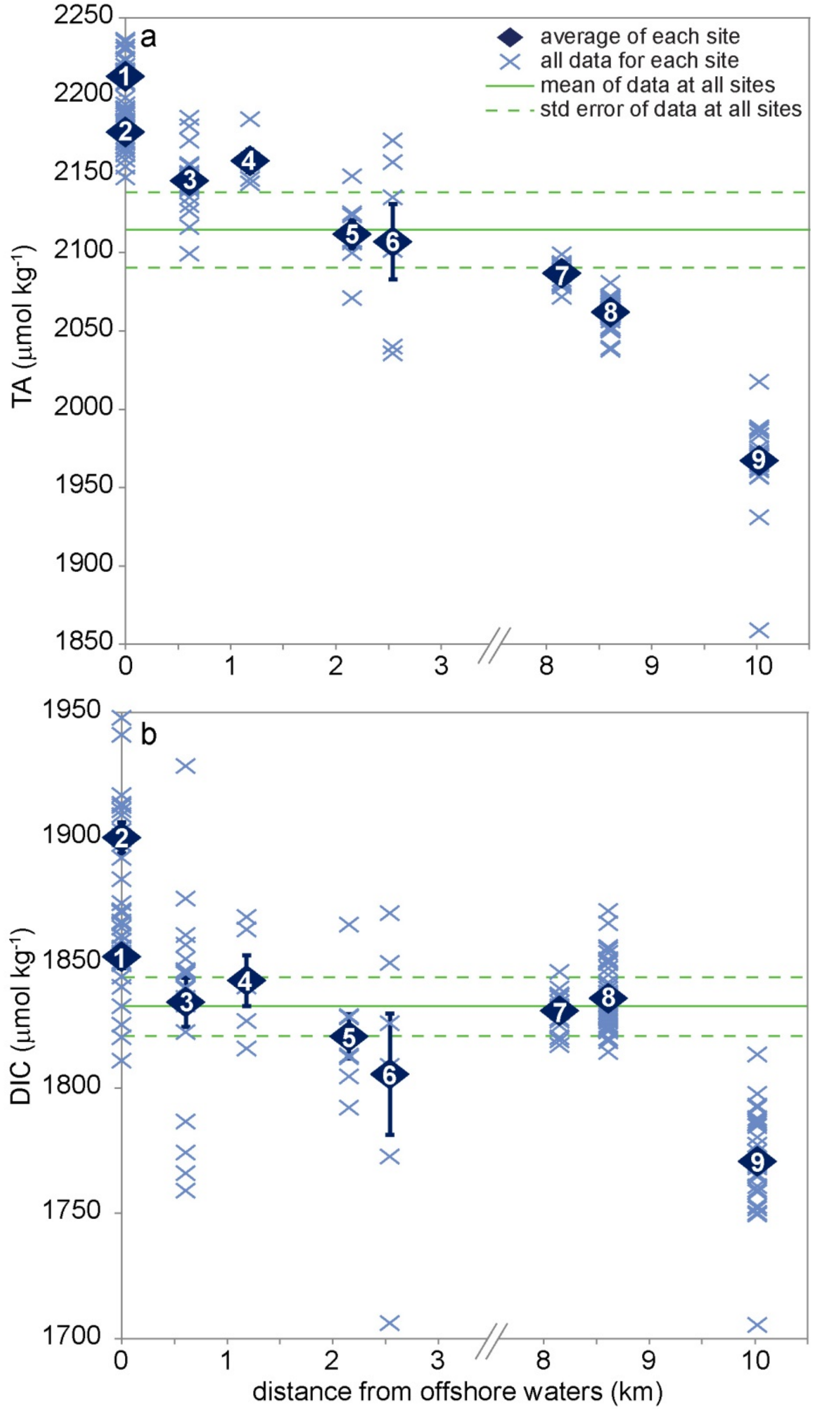

Figure S3. Average total alkalinity (TA) (a) and dissolved inorganic carbon (DIC) (b) ± 1 standard error (dark blue diamonds with error bars) and all data collected (blue crosses) for each site versus distance from offshore waters. Green horizontal lines represent the mean (solid line) TA (a) and DIC (b) of all sites ± 1 standard error of all sites (dashed green lines).

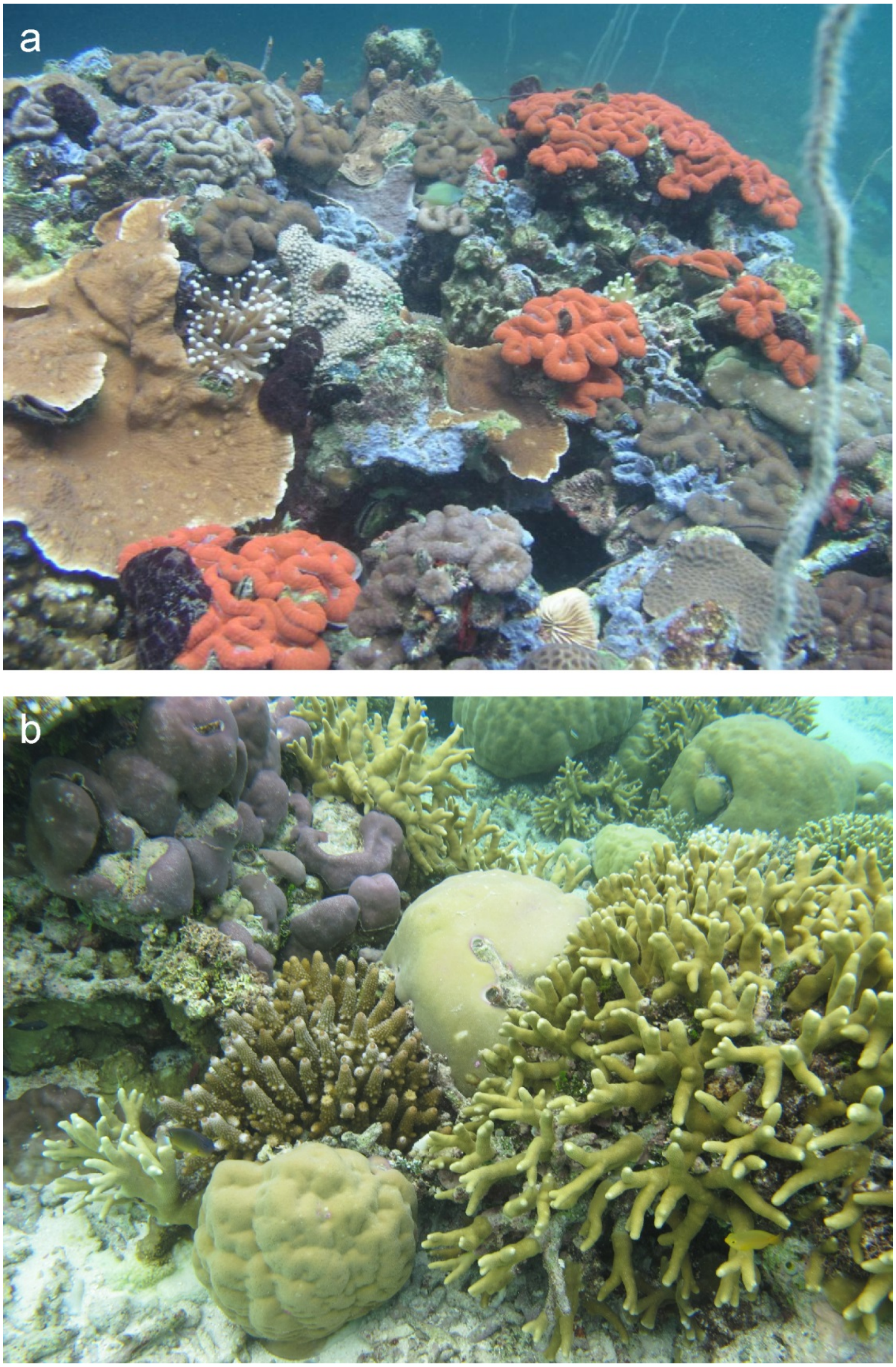

Figure S4. Photographs of Palauan coral reef communities. Site 9 (see Figure 1) in the Rock Islands where mean Ω_{ar} = 2.34 ± 0.04 (a) and the lagoon side of the southeastern barrier reef at site 3 (see Figure 1) where mean Ω_{ar} = 3.58 ± 0.08 (b).

Tables

Table S1. Average temperature, salinity, and carbonate chemistry data ± 1 standard error. Site numbers correspond to those in Figure 1.

site #	N	temp (°C)	salinity	TA (µmol kg^{-1})	DIC (µmol kg^{-1})	Ω_{ar}	pCO_2 (µmol)	pH	CO_3^{2-} (µmol kg^{-1})
1	18	29.5 ± 0.1	33.4 ± 0.0	2177.0 ± 3.7	1852.5 ± 4.6	3.73 ± 0.03	360.5 ± 4.6	8.05 ± 0.00	227.5 ± 1.8
2	17	28.9 ± 0.1	33.9 ± 0.1	2212.6 ± 4.7	1900.0 ± 6.2	3.60 ± 0.03	392.0 ± 6.3	8.03 ± 0.01	220.6 ± 1.9
3	18	29.6 ± 0.1	33.4± 0.0	2146.0 ± 5.0	1834.4 ± 9.8	3.58 ± 0.08	379.4 ± 15.8	8.03 ± 0.01	218.1 ± 4.9
4	7	29.7 ± 0.2	33.4 ± 0.1	2158.7 ± 7.2	1843.0 ± 10.1	3.64 ± 0.09	372.2 ± 11.1	8.04 ± 0.01	221.2 ± 5.3
5	7	29.7 ± 0.1	33.4 ± 0.1	2111.8 ± 9.2	1820.7 ± 8.9	3.34 ± 0.05	402.2 ± 9.6	8.00 ± 0.01	203.6 ± 3.0
6	6	29.6 ± 0.3	33.1 ± 0.3	2107.0 ± 23.9	1805.6 ± 24.1	3.46 ± 0.15	378.3 ± 19.6	8.03 ± 0.02	210.3 ± 8.9
7	17	29.5 ± 0.2	33.2 ± 0.0	2086.7 ± 1.6	1830.9 ± 1.9	2.97 ± 0.03	464.5 ± 4.1	7.95 ± 0.00	180.6 ± 1.7
8	51	30.0 ± 0.1	33.2 ± 0.0	2062.0 ± 1.0	1835.9 ± 1.7	2.66 ± 0.02	544.7 ± 4.5	7.89 ± 0.00	161.6 ± 1.0
9	26	30.2 ± 0.2	32.2 ± 0.1	1967.1 ± 5.3	1770.7 ± 4.3	2.34 ± 0.04	586.1 ± 7.5	7.84 ± 0.00	141.1 ± 2.2

Table S2. Average Ω_{ar} ± 1 standard error for a barrier reef site (site 3) and the Rock Island bay sites (sites 7-9) during incoming and outgoing tides and during the rainy (September) and dry (March) seasons. N is shown in parentheses. Site numbers correspond to those in Figure 1.

	site 3	site 7	site 8	site 9
September 2011:				
average all data	3.53 ± 0.10 (14)	2.92 ± 0.05 (9)	2.53 ± 0.06 (7)	2.37 ± 0.05 (18)
ave incoming tide	3.71 ± 0.13 (4)	2.94 ± 0.12 (3)	2.53 ± 0.04 (2)	2.36 ± 0.09 (6)
ave outgoing tide	3.48 ± 0.05 (5)	2.90 ± 0.08 (4)	2.53 ± 0.11 (4)	2.34 ± 0.11 (8)
March 2012:				
average all data	3.78 ± 0.11 (4)	3.03 ± 0.03 (8)	2.68 ± 0.02 (44)	2.28 ± 0.03 (8)
ave incoming tide	3.61 ± 0.09 (2)	2.94 ± 0.01 (2)	2.63 ± 0.04 (10)	2.24 ± 0.12 (2)
ave outgoing tide	-	3.09 ± 0.01 (4)	2.73 ± 0.02 (22)	2.29 ± 0.03 (5)