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End of the Century pCO₂ Levels Do Not Impact Calcification in Mediterranean Cold-Water Corals

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Abstract

Ocean acidification caused by anthropogenic uptake of CO₂ is perceived to be a major threat to calcifying organisms. Cold-water corals were thought to be strongly affected by a decrease in ocean pH due to their abundance in deep and cold waters which, in contrast to tropical coral reef waters, will soon become corrosive to calcium carbonate. Calcification rates of two Mediterranean cold-water coral species, *Lophelia pertusa* and *Madrepora oculata*, were measured under variable partial pressure of CO₂ (pCO₂) that ranged between 380 μatm for present-day conditions and 930 μatm for the end of the century. The present study addressed both short- and long-term responses by repeatedly determining calcification rates on the same specimens over a period of 9 months. Besides studying the direct, short-term response to elevated pCO₂ levels, the study aimed to elucidate the potential for acclimation of calcification of cold-water corals to ocean acidification. Net calcification of both species was unaffected by the levels of pCO₂ investigated and revealed no short-term shock and, therefore, no long-term acclimation in calcification to changes in the carbonate chemistry. There was an effect of time during repeated experiments with increasing net calcification rates for both species, however, as this pattern was found in all treatments, there is no indication that acclimation of calcification to ocean acidification occurred. The use of controls (initial and ambient net calcification rates) indicated that this increase was not caused by acclimation in calcification response to higher pCO₂. An extrapolation of these data suggests that calcification of these two cold-water corals will not be affected by the pCO₂ level projected at the end of the century.

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Introduction

Ocean acidification is one of the major threats to the marine environment and has become a central research focus in marine science during the last decade. The ocean and atmosphere exchange carbon dioxide (CO₂) [1], and the net uptake of CO₂ by the ocean causes the pH to decline. Due to anthropogenic activity, the ocean pH has already declined by 0.1 units since pre-industrial times and will further decline by about 0.4 units until the end of the century [2]. The concentration of CO₂ in seawater is steadily increasing at an unprecedented rate of change and it is anticipated that atmospheric CO₂ concentrations increase four-fold between 1750 and 2100, reaching values above 1000 ppm [3]. Many calcifying organisms will be affected by ocean acidification with a decrease of the growth of their shells or skeletons [4–7]. Also, reproduction and larval growth are thought to be impeded [8–10]. For tropical coral reefs, the predictions as to the detrimental effects of ocean acidification are almost unison and foresee a decline in reef growth [11–15] and a shift in species composition with a decrease in diversity [16,17]. On the other hand, it has been shown, that the response to ocean acidification can be highly variable for different taxonomic groups [18].

Investigations on cold-water corals or deep-sea corals are scarce. So far only three experimental studies on the effects of ocean acidification have been published. The rate of net calcification of *Lophelia pertusa* from Norwegian waters was shown to decline under future pCO₂ conditions [19,20], while no or even a positive long-term (6 months) response of net calcification was observed [20]. A third study investigated the short-term response of net calcification of the Mediterranean coral *Madrepora oculata* under pCO₂ values reflecting past, pre-industrial and future conditions. No effect on net calcification was found between ambient and elevated pCO₂, while calcification rates were twice as high under pre-industrial pCO₂ than under ambient or elevated pCO₂. This suggests that present-day calcification rates of *M. oculata* have already drastically declined since pre-industrial times [21]. Cold-water corals were initially thought to become affected by ocean acidification before their tropical relatives because they inhabit deeper and colder waters where the aragonite saturation state (Ω_a) is lower than in shallower, warmer regions [22]. More than 70% of cold-water coral communities are found in regions that will be undersaturated with respect to aragonite by the end of the century [23]. However, experimental as well as observational evidence has shown that some cold-water corals are able to cope and maintain positive

skeletal growth even in waters undersaturated in Ω_a [19,20,24]. Furthermore, the study of Form & Riebesell [20] found a decline of net calcification at elevated $p\text{CO}_2$ in a short-term experiment and a stimulating effect in a long-term experiment from which they concluded that the cold-water coral *L. pertusa* is able to acclimate to higher $p\text{CO}_2$. In the present study, the question of acclimation is addressed using a thorough experimental design in which net calcification of individual coral samples is repeatedly measured as a function of exposure time to respective $p\text{CO}_2$ levels. The two branching cold-water coral species present in the Mediterranean Sea, *L. pertusa* and *M. oculata* are investigated to discern whether one of the two species is more resistant than the other or has a higher potential for acclimation. In the Mediterranean Sea, *M. oculata* is more widespread than *L. pertusa* [25]. This could indicate that the prevailing conditions in the Mediterranean Sea are more favourable for *M. oculata* than for *L. pertusa* and this might result in a divergent species response to changing ocean pH. It is well known, that the distribution of cold-water corals is controlled by temperature within a range of 4 to 12°C [26]. In the Mediterranean Sea, the temperature at depths where cold-water corals occur ranges between 12.5 to almost 14°C [25,27] which is, therefore, above the common temperature range. Additionally, total alkalinity is higher in the Mediterranean Sea than open oceans and consequently absorbs more atmospheric CO_2 . It has been shown, that anthropogenic CO_2 has already affected the Mediterranean Sea and that the pH has decreased by 0.05 to 0.14 pH units, depending on the depth considered, since pre-industrial times [28].

Materials and Methods

The present study aimed at elucidating (1) the effect of an increase in CO_2 (ocean acidification) on rates of net calcification on the two Mediterranean cold-water coral species, *M. oculata* and *L. pertusa*, (2) to find out whether there is a species effect and (3) to evaluate short- (shock) and longer-term (acclimation) responses in calcification. This has been addressed by measuring net calcification before, immediately after and 1, 2, 3 and 9 months after $p\text{CO}_2$ has been adjusted.

Sampling and Experimental Set-up

During the MedSeaCan cruise in June 2009, the cold-water corals *L. pertusa* and *M. oculata* were sampled in the canyon of Lacaze Duthiers using a remotely operated vehicle (ROV) and the vessel MINIBEX (COMEX, France). Corals were sampled at water depths of 500 (42°32.98'N, 03°25.21'E), 267 (42°34.98'N, 03°24.15'E) and 260 m (42°35.07'N, 03°24.14'E). On board, corals were maintained in a plastic container (1040×640×515 mm) at a controlled temperature of $12.5\pm0.5^\circ\text{C}$ using a chilling unit attached to a water pump (1000 l h^{-1}). Corals were transported back to the laboratory and maintained in a climate room at 13°C until the experiments started in August 2009. Coral branches were sub-divided into smaller fragments (Table 1) and placed into vials of 4.5 or 8 cm inner diameter and a volume of ca 300 and 1000 ml. The vials were placed in 4 aquaria that served as water baths (13°C) as well as overflow basins for seawater from the vials. Each vial received running seawater (Mediterranean surface water with a salinity of 38) and air using silicone tubings of 0.5/2.5 and 1.0/3.0 mm inner/outer diameter, respectively. The seawater was filtered through 2 layers of micron bags (5 and 1 μm) into two 100 l storage tanks in a climate room which was set to 11°C. Temperature in the water baths containing the vials was maintained at $\pm0.1^\circ\text{C}$ using electronic temperature controllers

(Corema) and heaters (Tetratec® HT75). Temperature homogeneity was obtained by circulation pumps (JBL Pro Flow 500, 500 l h^{-1}). Seawater was distributed by gravity from the storage tanks to the vials at a flow rate of 32 ± 14 ml h^{-1} . Air was supplied through a small tube (ca. 8 cm height×0.7/1.0 cm inner/outer diameter) inserted vertically in the vials, preventing the bubbles to be in direct contact with the coral fragments and providing an airlift and mixing. The air was pre-mixed using mass flow controllers (MFCs, ANALYT MC-GFC17, 0–10 l for air and 0–10 ml for pure CO_2) and an air compressor (Jun-Air OF302-25B) at a flow rate of 4×1 l min^{-1} distributed to 4×21 vials. Corals were fed 3 times a week with freshly hatched *Artemia* larvae and 1 time a week with frozen krill. The water bath containing the vials and overflowing seawater was also adjusted to the target $p\text{CO}_2$ by bubbling with an air stone (HOBBY ceramic air diffuser, 150 mm). Prior to each feeding the seawater of the water bath with respective $p\text{CO}_2$ was filtered (Tetratec EX 1200, 1200 l h^{-1}) and the strong water flow generated by the filtration unit was used to clean vials and remove old prey and detritus.

Determination of Rates of Net Calcification

Before changing the $p\text{CO}_2$ levels in the experimental set-up, net calcification for each coral fragments was determined using the alkalinity anomaly technique [29] in order to provide an initial control (T_0) at ambient $p\text{CO}_2$. Subsequently, the CO_2 concentration of the air used to bubble the vials was adjusted to 4 $p\text{CO}_2$ treatment levels (A–D) with treatment A at 280 (low), B at 400 (ambient), C at 700 (elevated) and D at 1000 ppm (elevated) using the MFCs. To adjust to lower $p\text{CO}_2$ than ambient (treatment A, 280 ppm), soda lime was used to generate low- CO_2 -air (5–10 ppm) which was mixed with pure CO_2 . For treatment B ambient air was used and for treatment C (700 ppm) and D (1000 ppm) ambient air was mixed with pure CO_2 . The exact mixing of air or CO_2 -free air with pure CO_2 was adjusted by a LI-COR CO_2 -analyser (LI-6252). The pH in the different treatments during coral maintenance was monitored on a weekly base using a commercial pH module and electrode (IKS aquastar) which was calibrated to the NBS standard (buffers 4 and 7). This was done to control that treatment levels remained relatively constant, however, these measurements were not used to assess the carbonate chemistry, which was determined by analysis of A_T and C_T (see below for details) 1) during 2-day incubation to determine calcification rates via the alkalinity anomaly technique and 2) in maintenance vials containing corals and in blanks (vials without corals) after 9 months when net calcification rates were established using the buoyant weight technique.

To discriminate between short- and longer-term effects, net calcification was determined immediately after changing the $p\text{CO}_2$ by transferring coral fragments directly from ambient into incubation vials adjusted to target air- CO_2 mix (T_1) and at about monthly intervals during the first 3 months (T_2 , T_3 and T_4 , with 29, 57 and 89 days of exposure, respectively) using the alkalinity anomaly technique. Additionally, net calcification was again determined after approximately 9 months (267 ± 14 days) with the buoyant weight technique [30] using a balance (Mettler Toledo) with a precision of 1 mg.

For determination of net calcification rates using the alkalinity anomaly technique, corals and blanks (seawater without corals) were placed for 2 days in the same type of vials than those in which they were maintained but with a constant volume of 200 or 700 ml. To maintain $p\text{CO}_2$ levels constant vials were aerated with the same air- CO_2 mix that was also used during maintenance periods for treatments A–D. At the end of the incubation, seawater

Table 1. Initial size (polyp number and skeletal weight) and initial net calcification rates (G) at T_0 (before manipulating $p\text{CO}_2$) of the corals *L. pertusa* (LP) and *M. oculata* (MO) used in repeated incubations of $p\text{CO}_2$ treatment A–D.

$p\text{CO}_2$	Species	N	number of polyps		skeletal weight [g]		G [% d^{-1}]	
			mean \pm S.D	Range	mean \pm S.D	Range	mean \pm S.D	Range
A	LP	4	15.75 \pm 8.96	7–28	10.22 \pm 3.23	7.11–14.73	0.005 \pm 0.003	0.000–0.008
B	LP	4	15.75 \pm 11.30	5–31	7.88 \pm 8.87	1.80–20.94	0.012 \pm 0.009	0.005–0.025
C	LP	5	20.60 \pm 14.84	7–46	8.82 \pm 7.72	3.49–22.31	0.004 \pm 0.004	0.000–0.010
D	LP	5	15.00 \pm 7.38	7–25	10.14 \pm 7.68	1.55–20.47	0.004 \pm 0.005	0.001–0.012
A–D	LP	18	16.89 \pm 10.35	5–46	9.29 \pm 6.67	1.55–22.31	0.006 \pm 0.006	0.000–0.025
A	MO	4	90.50 \pm 80.32	17–185	7.88 \pm 8.69	1.33–19.87	0.017 \pm 0.004	0.013–0.021
B	MO	7	36.14 \pm 19.28	18–77	3.21 \pm 3.44	0.72–10.25	0.034 \pm 0.033	–0.001–0.093
C	MO	6	38.00 \pm 24.27	17–83	2.88 \pm 1.57	1.28–5.67	0.014 \pm 0.015	–0.014–0.030
D	MO	6	61.17 \pm 50.06	14–132	8.26 \pm 10.61	0.59–24.41	0.024 \pm 0.015	0.007–0.052
A–D	MO	23	52.61 \pm 45.94	14–185	5.25 \pm 6.80	0.59–24.41	0.023 \pm 0.022	–0.014–0.093

Means \pm S.D.

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was sub-sampled to determine inorganic nutrients, dissolved inorganic carbon (C_T) and total alkalinity (A_T) as described in Maier et al. [21]. Other parameters of the carbonate chemistry ($p\text{CO}_2$, pH on the total scale, pH_T , and Ω_a) were determined from C_T , A_T , temperature (13°C), salinity (38) and hydrostatic pressure (0) using the software package seacarb [32] (Table 2 and S1). Rates of net calcification were calculated from differences in A_T from blanks (seawater without corals incubated in parallel to coral samples) and coral incubations and were corrected for changes in the concentration of inorganic nutrients. For the incubation at T_3 , no samples for inorganic nutrient concentrations were taken. Therefore, the regression functions between calcification rates corrected (or uncorrected) for inorganic nutrient release (Figure S1) were used to make the nutrient correction for T_3 . Data were normalized to the initial skeletal dry weight of coral fragments and reported in % d^{-1} [21,31] using the exponential growth function $G \text{ [% d}^{-1}] = ((W_n/W_0)^{1/n} - 1) * 100$; with G = net calcification rate, W_n = Weight after n days, W_0 = initial weight and d time interval (days) for growth increment (alkalinity anomaly method = 2 days, buoyant weight method = 267 days).

Statistical Analysis

Statistical analyses were conducted using the software package Statistica 7.0. A repeated measures analysis of variance (ANOVA) was used. Only coral fragments for which net calcification rates were established at all time steps (T_0 – T_4 and buoyant weight after 9 months) were considered for analysis as this is a pre-requisite for repeated measures testing. Therefore N is the same for all repeated measurements (Table S1). For independent samples (non-repeated measures analyses) a one-way ANOVA comparison of carbonate chemistry between $p\text{CO}_2$ treatments or initial size and initial net calcification rates (T_0) was used. If applicable, a post-hoc test was performed using the Honest Significance Difference (HSD) test for either equal or unequal N . The respective statistical tests used are also given in the text, tables and figure legends. Values are given as mean \pm S.D. unless stated otherwise.

Results and Discussion

Initial Carbonate Chemistry, Concentration of Inorganic Nutrients and Calcification

For the initial incubation at ambient $p\text{CO}_2$ (T_0), the average A_T and C_T of blank controls (incubation without corals) was 2616 ± 27 and $2374 \pm 21 \mu\text{mol kg}^{-1}$ (\pm standard deviation, throughout this paper; $N=30$). pH_T , $p\text{CO}_2$ and Ω_a were 8.05 ± 0.03 , $447.3 \pm 31.7 \mu\text{atm}$ and 2.68 ± 0.16 , respectively. The concentrations of phosphate and ammonium were 0.03 ± 0.07 and $1.03 \pm 1.48 \mu\text{mol kg}^{-1}$ ($N=16$). A_T and C_T decreased during the 2-day incubations of both coral species; A_T was on average 2546 ± 47 and $2571 \pm 32 \mu\text{mol kg}^{-1}$ and C_T was 2333 ± 39 and $2356 \pm 41 \mu\text{mol kg}^{-1}$ ($N=23$ and 18), respectively. As a consequence, pH_T and Ω_a were also lower in coral vials than in blanks while $p\text{CO}_2$ increased (Table 2). For both species, pH_T was lower by 0.05 units and Ω_a was lower by 0.03, whereas $p\text{CO}_2$ increased by 52 for *M. oculata* and 60 μatm for *L. pertusa*. Cold-water corals can release significant amounts of inorganic nutrients [33], and phosphate concentrations increased by 0.413 and $0.483 \mu\text{mol kg}^{-1}$ to 0.44 ± 0.49 and $0.51 \pm 0.34 \mu\text{mol kg}^{-1}$, while ammonium increased by 6.80 and 3.81 $\mu\text{mol kg}^{-1}$ to 7.83 ± 4.97 and $4.84 \pm 5.17 \mu\text{mol kg}^{-1}$ for *M. oculata* and *L. pertusa* ($N=18$ and 22), respectively.

Before changing the $p\text{CO}_2$ to respective treatment levels A–D (low-high $p\text{CO}_2$), mean calcification rates were $0.006 \pm 0.006\%$ d^{-1} for *L. pertusa* ($N=18$) and $0.023 \pm 0.022\%$ d^{-1} for *M. oculata* ($N=23$) (Table 1). For both species, the rates of net calcification were significantly correlated with skeletal weight. Smaller coral fragments exhibit higher net calcification rates following a negative logarithmic trend (Figure S2). This negative dependence of size and age for cold-water coral calcification is in accordance with earlier studies [19,21,36]. However, despite the fact that we worked with a relatively large size range, neither size (weight or polyp number), nor initial calcification rates measured under ambient $p\text{CO}_2$ (Table 1) differed significantly between the coral fragments used in the four $p\text{CO}_2$ treatments (1-way ANOVA, $p \geq 0.15$) and net calcification rates were well within the range of earlier findings [19–21,34,35].

Table 2. Parameters of the carbonate chemistry for the total anomaly technique at T₀ (ambient air, prior to adjusting to respective pCO₂ levels) and at T₁–T₄ (immediately and 1, 2 and 3 months after adjusting pCO₂, respectively).

T	pCO ₂	Coral	A _T	C _T	pH _T	pCO ₂	Ω _a	PO ₄	NH ₄
treatment			[μmol kg ⁻¹]	[μmol kg ⁻¹]		[μatm]		[μmol kg ⁻¹]	[μmol kg ⁻¹]
0 all	blank		2616±27	2374±21	8.05±0.03	447±32	2.7±0.16	0.03±0.07	1.03±1.48
1–4 A	blank		2606±5	2313±3	8.14±0.01	349±6	3.2±0.04	0.11±0.12	3.93±0.31
1–4 B	blank		2598±15	2370±10	8.03±0.02	468±26	2.6±0.12	0.02±0.02	1.50±0.34
1–4 C	blank		2598±1	2438±5	7.88±0.02	688±27	1.9±0.07	0.03±0.02	0.77±0.63
1–4 D	blank		2602±6	2492±4	7.76±0.01	929±25	1.5±0.03	0.03±0.04	0.77±0.90
0 all	LP		2571±32	2356±41	8.00±0.07	507±93	2.4±0.30	0.51±0.34	4.84±5.17
1–4 A	LP		2483±54	2236±23	8.10±0.02	379±10	2.8±0.11	0.89±0.13	3.73±0.85
1–4 B	LP		2529±14	2315±11	8.00±0.01	489±13	2.4±0.06	0.79±0.09	4.02±0.40
1–4 C	LP		2495±62	2352±56	7.85±0.01	713±19	1.7±0.05	0.83±0.05	5.23±0.66
1–4 D	LP		2477±36	2387±31	7.73±0.02	969±25	1.3±0.08	1.26±0.08	5.44±0.63
0 all	MO		2546±47	2333±39	8.00±0.06	499±74	2.4±0.28	0.44±0.49	7.83±4.97
1–4 A	MO		2525±7	2256±11	8.10±0.02	380±12	2.9±0.11	0.78±0.07	9.13±3.39
1–4 B	MO		2528±19	2320±12	8.00±0.04	495±50	2.3±0.21	0.65±0.05	5.32±0.28
1–4 C	MO		2523±4	2375±6	7.86±0.02	707±52	1.8±0.06	0.73±0.04	6.25±0.54
1–4 D	MO		2506±12	2408±7	7.74±0.02	947±20	1.4±0.06	1.06±0.13	8.76±3.08

Blank is seawater incubated in parallel without coral (N≥4, see Table S1) and used to subtract from A_T of coral incubations to determine net calcification rates. LP is *L. pertusa*, MO is *M. oculata*. A_T and C_T (bold) were measured after 2-day incubations and other parameters were calculated from A_T, C_T, temperature of 13°C and salinity of 38 using the software package seacarb [31]. Values are means ± S.D. (N is given in Table 1).

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Carbonate Chemistry of Blanks after Adjusting pCO₂ Levels

After the CO₂ was adjusted to the 4 pCO₂ levels (A–D), the carbonate chemistry changed accordingly (Table 2). For the blanks, A_T was relatively uniform around 2600 μmol kg⁻¹ for treatments A to D. The C_T of blanks increased from 2313±3 to 2492±4 μmol kg⁻¹, and pH_T decreased from 8.14±0.01 to 7.76±0.01, Ω_a from 3.2±0.04 to 1.5±0.03 and pCO₂ levels ranged from 349±6 to 929±25 μatm for treatments A to D, respectively. For time step T₁–T₄, A_T was not significantly different between treatments A–D (One-way ANOVA, p>0.2), while it was significant between maintenance vials buoyant weight, treatment B and D, and buoyant weight, treatment D and T₄ treatment D. Other parameters of the carbonate chemistry (C_T, pCO₂, pH and Ω_a) were in general significantly different between single pCO₂ treatments (One-way ANOVA, Tukey Honest-Significant Difference (HSD) post-hoc test, p<0.05) with exceptions for adjacent treatment levels where p-values between treatments were >0.05. The actual pCO₂ values of seawater differed from those applied by the MFCs and revealed a reduced range between 349 to 929 instead of 280 to

1000 μatm, respectively. This is probably due to the fact that all 4 pCO₂ treatments were maintained and incubated in the same climate room and mixing of seawater with the overlying air most likely took place due to the vertical water circulation that was generated by the aeration system.

Carbonate Chemistry and Calcification Rates in Coral Incubation after Adjusting pCO₂ Levels

For coral incubation of T₁–T₄, the A_T of seawater containing *L. pertusa* was on average 2496±45, while A_T for *M. oculata* incubation was on average 2520±21 (Table 2 and Table S1). The C_T of *L. pertusa* increased from treatment A–D from 2236±23 to 2492±4 μmol kg⁻¹ while C_T of *M. oculata* increased from 2256±11 to 2408±7 μmol kg⁻¹ for treatment A to D, respectively. Similar as for the T₀, the DIC, pH_T and Ω_a were slightly lower in coral vials than in corresponding blanks while pCO₂ was higher (Table 2). This means, that also other parameters of the carbonate system than the A_T changed during the 2-day incubation as a consequence of coral calcification and metabolism. It is evident, that these shifts cannot be avoided as the determination of calcification rates is based on the fact, that the

precipitation of 1 mole CaCO_3 decreases the A_T by 2 mole and C_T by 1 mole [37]. Also, the CO_2 released by coral respiration and calcification into the surrounding seawater was apparently not completely equilibrated by aeration with respective air- CO_2 gas mix and the pCO_2 levels of coral vials increased by an average 20 to 40 μatm during the 2-day incubation (Table 2). The A_T decreased by about 100 μmole relative to blanks, and there was no significant difference of A_T between pCO_2 treatments or repeated incubation T_1 to T_4 at the end of incubation (Table S2). The excretion of inorganic nutrients by cold-water corals increases the A_T , i.e. it counteracts the decrease caused by calcification. Thus, calcification rates determined by the alkalinity anomaly technique are an underestimate of actual calcification rates if not corrected for. In a previous study using freshly collected cold-water corals it has been demonstrated that calcification rates of both species would be underestimated by 10% if inorganic nutrients were not taken into account [21]. In the present study, inorganic nutrient concentrations were used to correct calcification rates using the following linear equations: $G_{L.\text{persusa}} = 1.025 \cdot G_{\text{uncorrected}} + 0.00019$ ($R = 0.997$, $N = 81$, $p < 0.001$) and $G_{M.\text{oculata}} = 1.027 \cdot G_{\text{uncorrected}} + 0.00093$ ($R = 0.993$, $N = 102$, $p < 0.001$) (Figure S1). This means that the ratio of inorganic nutrient release to net calcification was 4-times higher for freshly collected corals than for corals maintained in aquaria.

Calcification Rates and pCO_2 Treatment Effects

After the pCO_2 had been adjusted to the intended treatment levels, calcification rates were measured immediately (T_1) and 1, 2 and 3 months (T_2 – T_4) after adjusting the pCO_2 levels using the alkalinity anomaly technique and additionally after 9 months using the buoyant weighing technique. Pooled data from repeated measurements (average T_1 – T_4) of alkalinity anomaly corresponding to approximately 3-months of coral growth and the buoyant weight after 9-months provided similar results and average calcification rates of *L. pertusa* slightly varied between treatments A and D from 0.011 ± 0.008 to $0.017 \pm 0.012 \text{ d}^{-1}$ for the alkalinity anomaly method and between 0.010 ± 0.008 and $0.021 \pm 0.037 \text{ d}^{-1}$ for the buoyant weight technique (Figure 1, Table S3). For *M. oculata* average values ranged between 0.023 ± 0.012 and $0.035 \pm 0.025 \text{ d}^{-1}$ and between 0.017 ± 0.014 and $0.038 \pm 0.057 \text{ d}^{-1}$ for the alkalinity anomaly and buoyant weight technique, respectively. For both coral species, there was neither a significant effect between methods used to measure calcification rates (time span of maintenance at respective pCO_2 levels) nor a significant pCO_2 treatment effect or a combined effect of methods (exposure time) and pCO_2 levels (Repeated measures ANOVA, $p > 0.05$, Table S4A). As we used two different methods to establish net calcification rates over mid-term and longer-term calcification, we provide a methods comparison for a similar time interval (mid-term) between alkalinity anomaly and buoyant weight showing that the 2 methods provide similar results (SI 1). These data were not included in the manuscript, as they do not comprise the same N, which is mandatory for the repeated measures design used here.

Short-term (Shock) and Longer-term (Acclimation) Response to Variable pCO_2

The experimental approach used in the present study was designed to discriminate between short-term “shock” effects due to fast changes in pCO_2 levels and longer-term acclimation response of net calcification. The results from repeated determination of calcification rates over time revealed no short-term, or long-term response in calcification to higher pCO_2 for either of the two species investigated (Figure 2). There was a continuous increase in

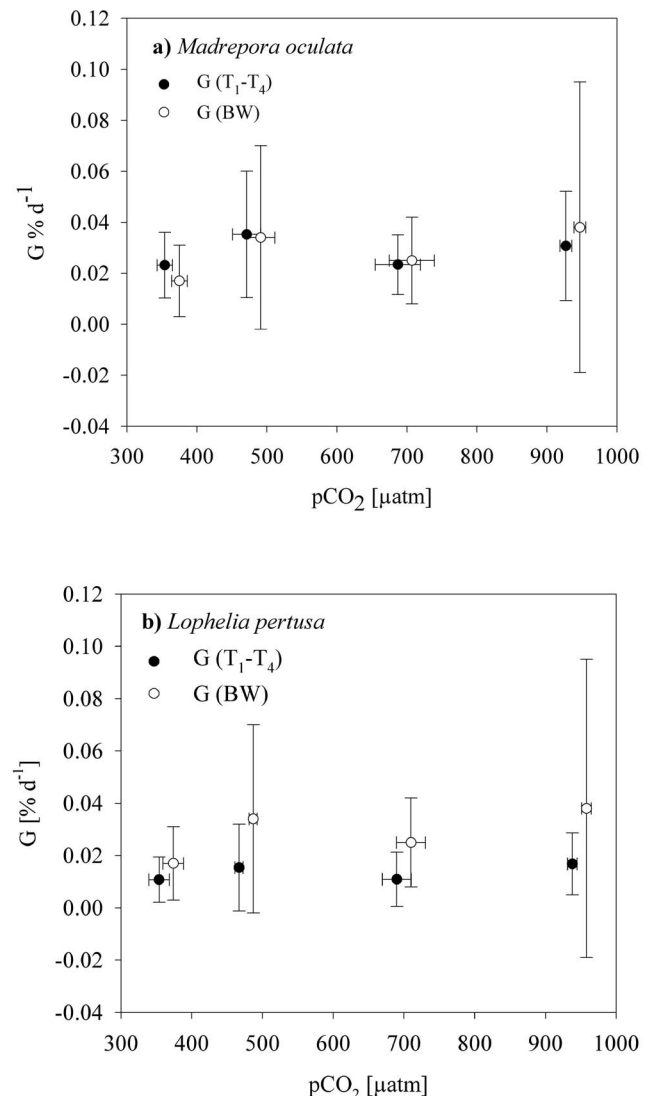


Figure 1. Net calcification rates of a) *M. oculata* and b) *L. pertusa* at various pCO_2 levels pooled over T_1 – T_4 (total anomaly technique) and from buoyant weight technique spanning 4 or 9 months, respectively. Values are mean \pm SD, $N \geq 4$ (Table 1). doi:10.1371/journal.pone.0062655.g001

calcification rates for the coral *L. pertusa* in treatment D which had highest pCO_2 levels (Figure 1), however this increase was statistically not significant (repeated measures ANOVA, Table S4B). Thus, our data do not support an earlier suggestion for a potential short-term shock response with long-term acclimation of net calcification rates as proposed by Form & Riebesell [20]. Yet, there was an effect of time on net calcification rates for both coral species. In general, average calcification rates (pooled for pCO_2 treatments) increased until T_3 and then decreased at T_4 again (repeated measures ANOVA, unequal N HSD, Table S4C). This pattern was independent of pCO_2 treatment and similar for *L. pertusa* and *M. oculata*. This indicates, that factors other than pCO_2 must have been responsible for the changes in calcification rates with time, that were either driven by intrinsic controls (e.g. reproductive cycles) or a general acclimation to the maintenance conditions in the vials or aquarium (independent of pCO_2).

The lack of pCO_2 treatment effects seems to contradict other studies reporting on a short-term calcification response of *L. pertusa*

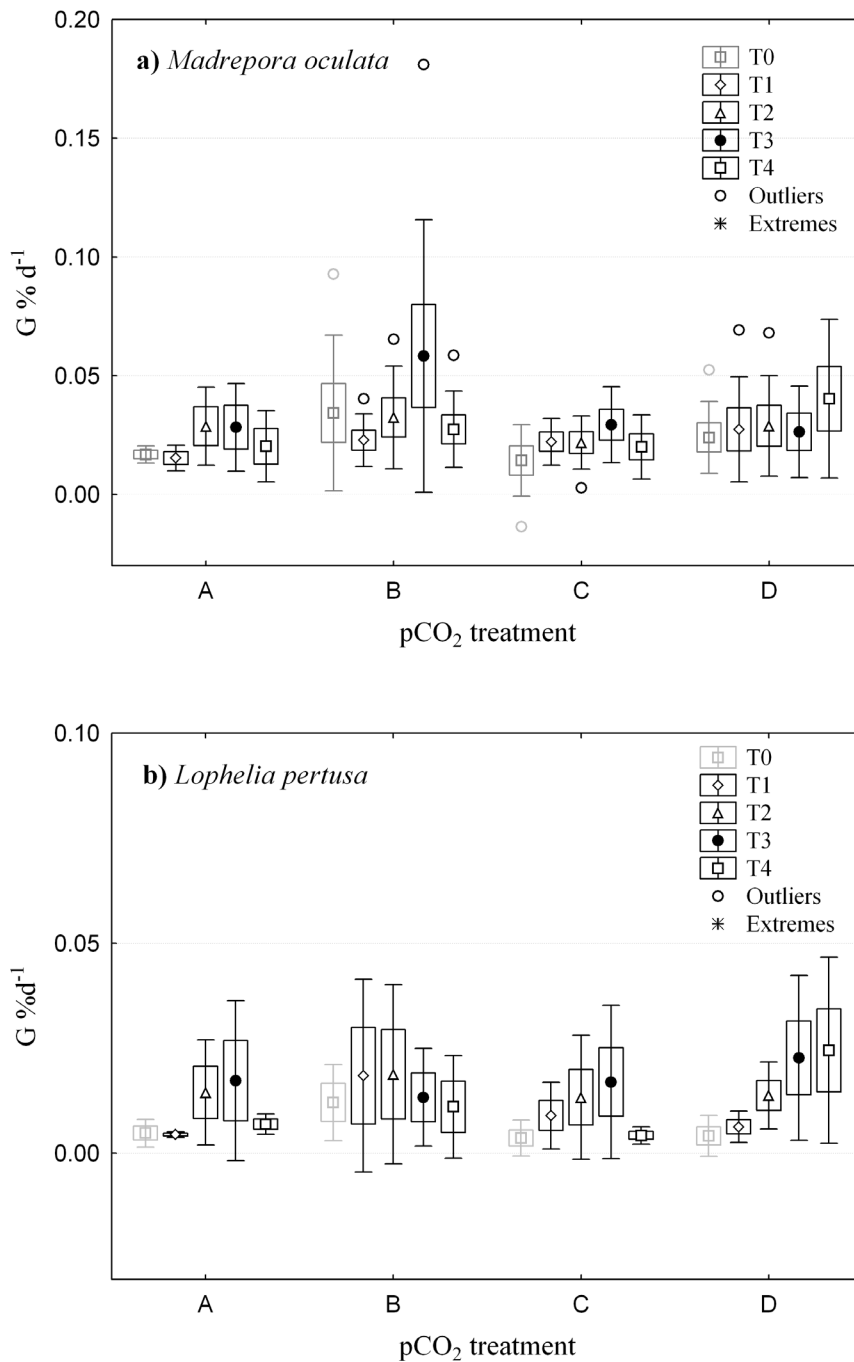


Figure 2. Net calcification rates (G) of a) *M. oculata* and b) *L. pertusa* at T₀–T₄ at the 4 pCO₂ treatment levels (pCO₂ values at different time steps and for the two species are given in Table S1). The pCO₂ at T₀ was at ambient pCO₂ and served as initial control, while T₁–T₄ was after pCO₂ has been changed to respective treatment levels. Values are mean \pm SE and SD.
doi:10.1371/journal.pone.0062655.g002

to elevated pCO₂ levels [19,20]. In the following, an attempt is made to reconcile these contradictory findings. Form & Riebesell found a negative correlation between calcification rates and CO₂ concentration in their short-term experiment. However, this negative correlation might have been due to one very high value for calcification rates at the lowest pCO₂ which forced the slope to a negative trend while all other values were within a certain range independent of pCO₂ ([20]; Figure 2) similar to the findings of the present study. In the short-term study by Maier et al. [19] there

was also a clear negative response to increasing pCO₂ on net calcification rates. In that study, the experimental set up was different as very small incubation vials (50 ml) and a closed system approach was used. Thus, the initial values for carbonate chemistry were comparable with the present study and that of Form & Riebesell [20], however, the carbonate chemistry changed drastically during incubation and mean pCO₂ values as high as 2160 μ atm were reached ([19]; Table S4). The conclusion with respect to an expected 50% decrease in calcification rates by the

end of the century might thus have been a misinterpretation with respect to relating net calcification rates to the initial $p\text{CO}_2$ range and not to the much higher $p\text{CO}_2$ values that were actually reached during incubation due to the closed system approach and small incubation volume.

For *M. oculata*, so far only one study exists with respect to ocean acidification and it addresses the short-term $p\text{CO}_2$ effect on net calcification rates [21]. In that study, the $p\text{CO}_2$ was changed in two ways: 1) to that of pre-industrial concentrations (285 ppm) and 2) to values projected for the end of the century (865 ppm). Similar to the present study, there was no change in net calcification rates between ambient and future $p\text{CO}_2$ levels, while calcification rates doubled when $p\text{CO}_2$ was set to values of pre-industrial times indicating that the increase in $p\text{CO}_2$ that took place since pre-industrial times had already a negative impact on *M. oculata* calcification.

The results of the present study are in contrast to the acclimation hypothesis postulated by Form & Riebesell [20]. Their conclusion with respect to acclimation was based on the fact, that there was a negative short-term response, while in the long-term study higher $p\text{CO}_2$ had even higher calcification rates than the two lower $p\text{CO}_2$ levels. However, there is indication that their data can be interpreted differently. First, the long-term experiment of Form & Riebesell [20] lacked the ambient $p\text{CO}_2$ control and did thus not cover the same $p\text{CO}_2$ range than their short-term study. However, an ambient $p\text{CO}_2$ treatment in the long-term study would have been pivotal, specifically because the negative response in the short-term experiment was caused by a higher calcification rate at ambient $p\text{CO}_2$. Second, the study by Form & Riebesell [20] also lacked initial controls. It is therefore possible, that the coral fragments used in the high $p\text{CO}_2$ treatment had already higher initial calcification rates under ambient $p\text{CO}_2$ conditions. In contrast, the experimental design of the present study comprised both initial and ambient controls and a time-series for calcification rates which allowed a better evaluation of shock or short-term responses versus long-term acclimation in calcification rates. Due to a lack in short-term response of calcification for the range in $p\text{CO}_2$ levels studied, our data do not provide evidence that acclimation had played a role in the long-term calcification response to increasing $p\text{CO}_2$. This does not mean that no acclimation took place, it rather means that the mechanism(s) enabling cold-water corals to maintain calcification rates constant over a large $p\text{CO}_2$ range (independent of the duration of the exposure) remain to be identified.

Summary View of $p\text{CO}_2$ Effects on Cold-water Coral Calcification

For a $p\text{CO}_2$ range between 350 and 1000 μatm , no effect on net calcification rates, neither for short- nor long-term exposure could be distinguished, and there is evidence that the recently postulated cold-water coral acclimation hypothesis [20] does not hold as such. The present study revealed significant changes observed as function of time for all $p\text{CO}_2$ treatments, but this must be attributed to other causes than $p\text{CO}_2$ either related to aquarium conditions or coral biology. Including the previous 3 studies on cold-water coral response to ocean acidification and the results of the present study a certain pattern emerges: the response of cold-water corals *L. pertusa* and *M. oculata* to increasing $p\text{CO}_2$ is non-linear and net calcification rates remain constant for a $p\text{CO}_2$ range between ambient and somewhere above 1000 μatm where Ω_a is already close to or even below 1. The negative short-term response in the study by Maier et al. (2009) indicated, that once a threshold at high $p\text{CO}_2$ has been reached, a significant decline in net calcification rates can be expected with increasing $p\text{CO}_2$ it can

further be assumed that this threshold lies somewhere below 2000 μatm . For the Mediterranean coral *M. oculata* it appears that a 1st threshold had already been surpassed since pre-industrial as indicated by the increase in calcification rates of *M. oculata* at reduced $p\text{CO}_2$ [21]. In this respect, the exceptionally high calcification value of *L. pertusa* at lowest $p\text{CO}_2$ in the short-term experiment of Form & Riebesell [20] might be indicative of such a threshold between present-day and pre-industrial $p\text{CO}_2$, however, this needs further investigation.

A non-linear response is contrary to findings for tropical, zooxanthellate corals, that generally reveal a linear, negative calcification response to increasing $p\text{CO}_2$ [13–15]. However, a non-linear response had already been revealed for temperate zooxanthellate corals which, similar to the Mediterranean cold-water corals, remained unaffected within a large range of present-day to end of the century projections of $p\text{CO}_2$ [18,38,39] and a drastic reduction in calcification at a $p\text{CO}_2$ of 2850 μatm [40]. The responses of the organisms to increasing ocean acidification are variable and complex [18] and even enhanced calcification at higher $p\text{CO}_2$ had been proposed for some taxa [41–43].

Up to now it is unclear how the corals are able to resist increasing $p\text{CO}_2$ levels and how they maintain calcification rates constant over such a large $p\text{CO}_2$ gradient. It has been proposed that cold-water corals are able to resist increasing ocean acidification by their ability to maintain a high pH within their calcicoblastic, calcifying fluid [44]. The way the calcifying fluid is sheltered and replenished with cations from ambient seawater is crucial in how a coral responds to increasing ocean acidification [45–46]. Also, an explanation why temperate corals can resist to higher $p\text{CO}_2$ levels are their lower growth rates [38] as less carbonate ions will be required in the same time for calcification. This could also explain why cold-water corals grow in waters with an Ω_a around 1, while fast growing tropical corals are found in waters with an Ω_a above 3.5. Overall, cold-water corals seem well adapted to low Ω_a which may explain their resistance to increasing $p\text{CO}_2$ levels up to a certain threshold. Tropical corals can experience drastic short-term changes of $p\text{CO}_2$ in the close environment due to diurnal changes in CO_2 uptake and release driven by light-dependent changes in the metabolic functioning of reef organisms [47]. Nothing is known on naturally occurring short-term changes in the seawater carbonate chemistry close to cold-water corals but due to the lack of photosynthetic activity in these depths they are likely less pronounced than in tropical reef systems. Nevertheless the question remains if any naturally occurring short-term changes render cold-water corals resistant to fast changes in $p\text{CO}_2$ and a large range of $p\text{CO}_2$ with values reaching more than 1000 μatm . Finally, it is still questionable if acclimation of calcification to increasing $p\text{CO}_2$ is a likely scenario in the natural environment. The resistance to increasing $p\text{CO}_2$ levels and the maintenance of constant calcification requires energy and might thus be sustainable during short-term exposure while energy requirements might not be sustained over longer time of exposure to higher $p\text{CO}_2$. This might especially be the case in the natural cold-water coral environment, where regular food supply as usually provided during aquarium maintenance is not always guaranteed and where other stressors such as predation, disease and temperature abnormalities may further impede coral growth.

Supporting Information

Figure S1 Calcification rates (G) of *M. oculata* and *L. pertusa* corrected and uncorrected for inorganic nutrient release during incubation. Correlation analysis were

significant with $R = 0.993$, $N = 102$, $p < 0.001$ and $R = 0.997$, $N = 81$, $p < 0.001$ for *M. oculata* and *L. pertusa*, respectively. (PDF)

Figure S2 Calcification rates (G) versus skeletal weight (SW) of *M. oculata* and *L. pertusa* under ambient pCO₂ conditions (T₀). Logarithmic regressions are significant with $p = 0.01$ for both species; $N = 23$ and 18 for *M. oculata* and *L. pertusa*, respectively. (PDF)

Table S1 Parameters of the carbonate chemistry (CC) and the inorganic nutrients (IN) phosphate (PO₄) and ammonium (NH₄) for the incubation times T₀–T₄ and pCO₂ treatments A–D after 2-day incubation using the alkalinity anomaly technique. Additionally, CC was established after 9 months (267 days) when net calcification rates were measured using the buoyant weight (BW) technique. T₀ was established prior to adjusting pCO₂ at ambient for all treatments, while T₁–T₄ and BW are values derived from 2-day incubations immediately and 1, 2 and 3 months after adjusting pCO₂ and after 9 months, respectively. LP (*Lophelia pertusa*), MO (*Madrepora oculata*) and blank (incubated in parallel without coral) at respective pCO₂ treatment levels. Values are given as mean \pm S.D. (PDF)

Table S2 Post-hoc results (Tukey honest-significance difference test for unequal N) of breakdown ANOVA for parameters of the carbonate chemistry (A_T, C_T, pCO₂, pH_T, Ω_a) for the coral incubations with T₁–T₄ (directly and 1, 2, 3 months after pCO₂ was changed to respective treatment levels) established during 2-day incubation using alkalinity anomaly and after 9 months (267 days) using buoyant weight (BW) technique to determine net calcification rates. Matrix of p-values for *L. pertusa* at upper right and for *M. oculata* at lower left part of the table with $p < 0.05$ (italic). Bold values are corresponding treatments at different incubation times. (PDF)

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Table S3 Average calcification rates (G) of the cold-water corals *Lophelia pertusa* (LP) and *Madrepora oculata* (MO) at T₀ to T₄ determined by the total anomaly technique in monthly time intervals and 2 days of incubation, and calcification rates determined by buoyant weight (G/BW) after maintenance of corals for 9–10 months under respective pCO₂ treatment levels. (PDF)

Table S4 Statistical results for repeated measures ANOVA of calcification rates (G). A Comparison between total alkalinity (TA) method (average G, pooled T₁–T₄) and Buoyant Weighting (BW) for pCO₂ treatments A–D; and B for comparison of repeated measurements T₀–T₄ for the 4 pCO₂ treatments. Table C gives the matrix for p-values of the Tukey–Honest-Significance post-hoc comparison for unequal N of the variable R₁ (T₀–T₄) for *M. oculata* (lower left) and *L. pertusa* (upper right). Significant p are marked in bold, italic (PDF)

File S1 Method comparison between total alkalinity anomaly (TAA) and buoyant weight (BW) technique to establish net calcification rates (G) of *M. oculata* and *L. pertusa*. (PDF)

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Author Contributions

Conceived and designed the experiments: CM MW JPG PW. Performed the experiments: CM AS MMBS. Analyzed the data: CM AS MMBS. Contributed reagents/materials/analysis tools: CM JPG MW PW. Wrote the paper: CM.

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