

Effect of CO₂-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.)

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Abstract. Oceanic uptake of anthropogenic CO₂ results in a reduction in pH termed “Ocean Acidification” (OA). Comparatively little attention has been given to the effect of OA on the early life history stages of marine animals. Consequently, we investigated the effect of culture in CO₂-acidified sea water (approx. 1200 ppm, i.e. average values predicted using IPCC 2007 A1F1 emissions scenarios for year 2100) on early larval stages of an economically important crustacean, the European lobster *Homarus gammarus*. Culture in CO₂-acidified sea water did not significantly affect carapace length of *H. gammarus*. However, there was a reduction in carapace mass during the final stage of larval development in CO₂-acidified sea water. This co-occurred with a reduction in exoskeletal mineral (calcium and magnesium) content of the carapace. As the control and high CO₂ treatments were not undersaturated with respect to any of the calcium carbonate polymorphs measured, the physiological alterations we record are most likely the result of acidosis or hypercapnia interfering with normal homeostatic function, and not a direct impact on the carbonate supply-side of calcification *per se*. Thus despite there being no observed effect on survival, carapace length, or zoeal progression, OA related (indirect) disruption of calcification and carapace mass might still adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function.

1 Introduction

The ocean is a substantial reservoir of CO₂ (Feely et al., 2004; Sabine et al., 2004; Morse et al., 2006). Addition of CO₂ to sea water alters the carbonate chemistry and reduces pH, in an effect recently termed “Ocean Acidification” (OA). Over the past 200 years increasing *p*CO₂ has resulted in a decrease in surface sea water pH of 0.1 units (Caldeira and Wickett, 2003; Orr et al., 2005). It is predicted that atmospheric CO₂ concentrations could reach 1200 ppm by the year 2100 resulting in a decrease in average surface ocean pH of 0.3 to 0.4 units (Caldeira and Wickett, 2003; Raven et al., 2005). Our understanding of the biological and ecological consequences of OA is, however, still in its infancy (Raven et al., 2005). Reductions in seawater pH have been demonstrated to affect the physiological and developmental processes of a number of marine organisms (e.g. Pörtner et al., 2004, 2005; Raven et al., 2005) through reduced internal pH (acidosis) and increased CO₂ (hypercapnia), raising the possibility that not only species, but also ecosystems, will be affected (Widdicombe and Spicer, 2008).

As CO₂ increases and pH decreases there is a concomitant reduction in carbonate ion (CO₃²⁻) availability, which can lead to increased dissolution of calcium carbonate (CaCO₃) structures. This may have a significant impact on species, which have CaCO₃ skeletons, such as reef building organisms, some phytoplankton, molluscs, crustaceans and echinoderms. Research into the effects of OA has thus far primarily investigated impacts on these calcareous marine organisms, particularly focusing on corals (e.g. Reynaud et al., 2003; Langdon and Atkinson, 2005), molluscs (e.g. Michaelidis et al., 2005; Gazeau et al., 2007) and coccolithophores



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(e.g. Riebesell, 2000; Zondervan et al., 2002; with reviews by Paasche, 2001; Hinga, 2002; and Riebesell, 2004). Studies to date have demonstrated a number of potentially important effects including reduced growth rates (Gazeau et al., 2007), decreased reproductive success (Kurihara et al., 2004b), shell dissolution (Bamber, 1990) as well as acidification of internal body fluids (Spicer et al., 2007), compromise of induced defences (Bibby et al., 2007), increased susceptibility to infection (Holman et al., 2004) and impairment of immune function (Bibby et al., 2008). Unfortunately the majority of these studies have investigated short-term responses with most attention being paid to effects on adult organisms alone. Thus there is an urgent need, both for more long-term data, especially for invertebrates (Langenbuch and Pörtner, 2002; Pörtner et al., 2004; Michaelidis et al., 2005) and studies of species at different stages of their larval development as well as on adults (Widdicombe and Spicer, 2008). Research into the effects during larval stages has mainly focused on echinoderms (Kurihara and Shirayama, 2004; Havenhand et al., 2008; Dupont et al., 2008), fish (Ishimatsu et al., 2004), copepods (Kurihara et al., 2004b, 2007), amphipods (Egilsdottir et al., 2009) and gastropods (Ellis et al., 2009). However, it is important to investigate potential effects of CO₂-induced acidification during early life stages, as they are likely to be more sensitive to such environmental stressors than adults (e.g. Kikkawa et al., 2003; Ishimatsu et al., 2004), especially as many benthic species possess pelagic larval stages which occur in the surface waters where increasing *p*CO₂ is occurring first (Calderia and Wickett, 2003). Determining how OA might affect larval development of benthic organisms, particularly those that initiate calcification processes while still in their planktonic phase, is critical to predicting how these impacts might propagate through the ecosystem. Early investigations suggest that early life stage development may be slowed (Egilsdottir et al., 2009; Findlay et al., 2009) or even completely disrupted (Dupont et al., 2008; Havenhand et al., 2008) at CO₂ levels predicted for the end of this century.

The European lobster *Homarus gammarus* is an economically important species contributing substantially to the continued survival of small coastal communities. Calcification in the Norway lobster *Nephrops norvegicus*, closely related to *H. gammarus*, occurs during very early development, with a major change in the pattern of calcification observed as the individual makes the transition from a planktonic zoea to a benthic postlarva (Spicer and Eriksson, 2003). While crustacean exoskeletons contain CaCO₃, this most likely predominates in the more soluble polymorph, magnesium calcite (Mg-CaCO₃) (Boßelmann et al., 2007). It is believed that crustaceans utilise either CO₂ or bicarbonate (HCO₃⁻), not carbonate (CO₃²⁻) as the primary source of carbon for the formation of their CaCO₃ structures (Cameron, 1989). Therefore reduction in CO₃²⁻ as a result of OA may not always be expected to directly impact their ability to produce CaCO₃. *H. gammarus* is cultured within hatcheries to aid

commercial catch and hence is an ideal model to use to understand the impacts that OA might have on the early development stages of a commercially important crustacean. Consequently, this study investigated the effect of CO₂-induced acidification on the early life stages of *H. gammarus*. The patterns of growth and shell mineralogy of the carapace during larval development were determined by measuring the length, area, dry mass and Ca and Mg contents of the carapace. As Mg-CaCO₃ is more soluble than other polymorphs of calcium carbonate, aragonite and calcite, (Feely et al., 2004) it may be less advantageous to form Mg-CaCO₃ under decreasing pH as it will be the first to dissolve (Kleympas et al., 2006), hence these lobsters may be at greater risk from dissolution. Exposure to long-term hypercapnia may be energetically costly to marine organisms and therefore may be detrimental to developmental processes, such as growth, reproduction, natural recruitment and survival (Barry et al., 2005; Wood et al., 2008).

2 Materials and methods

2.1 Animal material

Ovigerous females were supplied by local fishermen and held in aquaria (160×100×35 cm) at the National Lobster Hatchery (NLH) in Padstow, Cornwall, UK. Each aquarium was constantly supplied with aerated, filtered re-circulating sea water ($T=17\pm 1^\circ\text{C}$, $S=35$) pumped directly from waters adjacent to the NLH. Water was pre-treated in a pressurized sand filter, passed through activated carbon, and finally UV-irradiated. Adult lobsters were fed *ad libitum* with blue mussels, *Mytilus edulis*. Experiments were carried out between June and July 2007, to coincide with the natural hatching season (between April and September).

Sea water was placed in ten open conical flasks (vol.=1 l) and the CO₂ concentration was modified by equilibrating the water with air containing different CO₂ concentrations exactly as described by Findlay et al. (2008). Air/CO₂ mixtures were produced using a bulk flow technique where known amounts of scrubbed air (CO₂ removed using KOH) and CO₂ gas were supplied, *via* flow meters (Jencons, UK, Roxspur, France), and mixed before equilibrating with sea water. Control flasks were aspirated (10 l min⁻¹) with an air mixture containing 380 ppm of CO₂, however the pressure was not high enough to completely equilibrate these flasks, which had high alkalinity, and hence the measured sea water CO₂ value was slightly lower (mean 315 ppm). To produce the reduced pH treatment, sea water was aspirated (1 ml min⁻¹ CO₂ mixed with 10 l min⁻¹ scrubbed air) with the high-CO₂ air containing 1200 ppm of CO₂. The *p*CO₂ was monitored regularly using a *p*CO₂ micro-electrode (LazarLabs) and pH using a pH probe (Denver). Any fluctuations in pH were noted, and adjusted, *via* the flow meters, accordingly.

Newly-hatched Zoea I larvae, from 3 different mothers, were (carefully) distributed haphazardly between a number of aquaria (flasks vol.=1l; $N=50$ zoea per flask; $T=17\pm 1^\circ\text{C}$), with all flasks containing larvae from all females. Flasks contained one of the following aerated media: sea water (“untreated control”) or sea water with elevated CO_2 (1200 ppm) ($N=5$ for each treatment). Both treatments commenced simultaneously and were incubated for 28 days. Media changes were performed every 24 h. The elevated CO_2 treatment flasks were left to equilibrate for 2 h to the required CO_2 levels before larvae were transferred to them. Both moulted exoskeletons and mortalities were removed before changing media. Larvae were fed (*Artemia* nauplii, density=5 indiv ml^{-1} sea water) after media changes (Carlberg and Van Olst, 1976).

2.2 Larval growth and development

Larvae were removed haphazardly from each flask ($N=9$), at day 7, 14, 21 and 28. Larval development can vary depending on temperature; therefore in order to ascertain larval development times under the control conditions, preliminary studies were first carried out. The sampling days represent the mid-point of development through each of the four larval stages (i.e. Zoea I, II, III, and IV). Individuals were washed briefly in distilled water, carefully blotted dry with paper tissue, and stored frozen ($T=-20^\circ\text{C}$). They were subsequently freeze-dried (LYOVAC GT2, Leybold-Heraeus, Germany) to a constant mass, before the carapace was carefully removed and weighed using a microbalance (AT200, Mettler-Toledo, Switzerland). Carapace length (CL) and carapace area (CA) were measured using digital photographs under lower power magnification ($\times 10$) and ImageJ software. CL was calculated as shown in Fig. 1, CA was calculated by taking measurements of the removed and flattened carapace again using digital photography under lower power magnification ($\times 10$) and ImageJ software. Larval survival was observed daily, along with moult stage, which was recorded as a measure of development, and determined using the schemes of Aiken (1973) and Chang et al. (2001); this involves detailed examination of the exoskeleton and pleopods.

2.3 Carapace mineral content

Measurements of the calcium and magnesium content of the carapace from the same individuals measured above, for each of the four developmental stages (Zoea I, II, III, and IV), were made using Inductively Coupled Plasma Spectrometry (ICP). After the morphological measurements were made the carapace was dissolved in concentrated nitric acid (75% pro analysis) to extract the mineral portion. The resultant solution was diluted with Milli-Q water before ICP analysis. To compare between treatments and stages (these are relative measures and not absolute measures) the calcium and magnesium concentrations are expressed both as a percent-

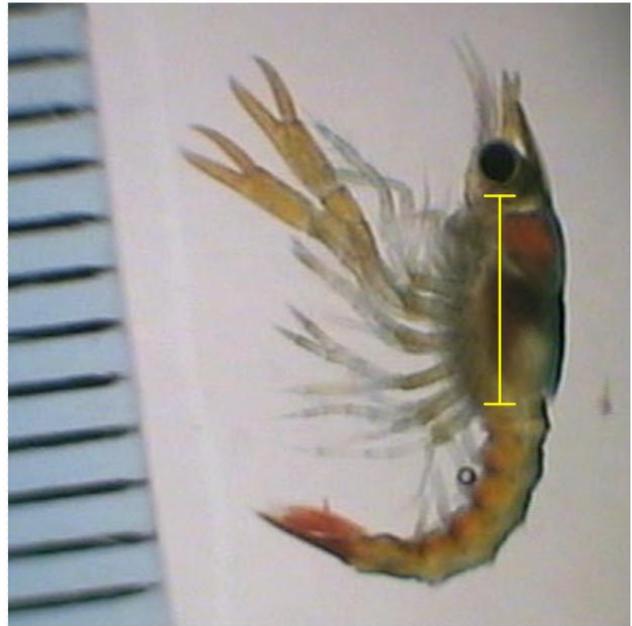


Fig. 1. Larval carapace length measured using digital photography under lower power magnification ($\times 10$) and image J software.

age of total mass of animal carapace and also per unit of total carapace area, exactly as presented by Spicer and Eriksson (2003). This gives an indication of the content of each mineral as the animal grows relative to the previous development stage and the percentage of total mass takes into account any differences in the thickness of the carapace.

2.4 Statistical analysis

Data are expressed as mean ± 1 S.E.; the data were tested for normality using the Kolmogorov-Smirnov test and homogeneity of variances and applying Levene’s test prior to analysis. Two-way repeated-measures ANOVA was used to investigate significant differences in physiological parameters as a result of CO_2 and of exposure time, and least significant difference *post hoc* tests were carried out to assess the significance of differences between treatment groups.

3 Results

3.1 Larval growth and development

There were no significant effects of hypercapnia on carapace length in larval *H. gammarus* ($p>0.05$) when expressed against time and developmental stage (Fig. 2a and b). There was however, an observed effect of hypercapnia on carapace mass throughout larval development, causing a significant reduction in mass at Zoea IV ($p<0.05$, Fig. 2c). As larvae were removed for sampling throughout the experiment, survival could only be observed during experimental exposures.

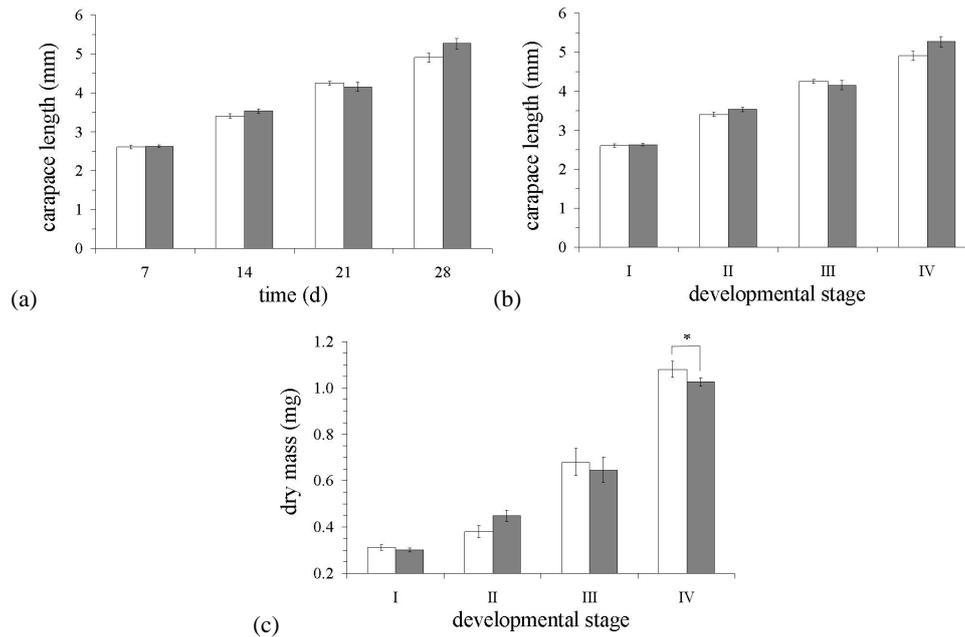


Fig. 2. Relationships between growth and development for larval *H. gammarus* during exposure to CO₂-acidification (1200 ppm). **(a)** Carapace length (mm) and development time (days); **(b)** Carapace length (mm) and developmental stage; **(c)** Carapace mass (mg) and developmental stage. Values represent mean±1 standard error; white, control; grey, 1200 ppm of CO₂.

From these observations, incubation with CO₂ did not appear to have an effect on the survival of larval lobsters.

3.2 Carapace mineral content

Changes in calcium concentration of the carapace during larval development are presented in Fig. 3. The calcium content in the carapace was significantly effected over time, with respect to treatment, this was detectable both when expressed as concentration per surface area ($p < 0.05$; Fig. 3a) and when presented as a percentage of the total carapace content ($p < 0.05$; Fig. 3b). In the high CO₂ treatment, the calcium concentration was almost half of the control at Zoea IV ($0.13 \mu\text{g mm}^{-2}$ S.E. 0.01 vs. $0.23 \mu\text{g mm}^{-2}$ S.E. 0.01). This indicates that after metamorphosis into Zoea IV the increased CO₂ significantly impacted the carapace calcium content.

The effect of increased CO₂ on magnesium in the carapace, when expressed as a concentration per surface area (Fig. 4a), produced a reduction in concentration over time when compared to the control, with significant differences occurring at Zoea IV ($p < 0.05$). Reduction in magnesium concentration, due to culture in CO₂-acidified sea water, were also apparent when expressed as a percentage of total carapace content ($p < 0.05$), with significant differences evident at Zoea III (Fig. 4b); 0.81% (S.E. 0.07) compared to 1.16% (S.E. 0.13) in the control larvae.

4 Discussion

4.1 Growth and carapace mineralogy

This is the first study, to the authors' knowledge, to document net changes in the calcium and magnesium content of the carapace of any lobster species during larval development. We found that larval length, area and mass of the carapace are coupled with development stage of the zoea larvae; and that there are progressive changes in the content of calcium and magnesium. Calcium and magnesium form the principal mineral portion of the crustacean exoskeleton (Neufeld and Cameron, 1992); the concentrations of which are most likely to be determined by environmental conditions (Wickins, 1984). The pattern of calcification displayed by *H. gammarus* generally follows a net increase in calcium as the larvae moult through each progressive zoea, with metamorphosis into the Zoea IV containing the largest concentration of calcium. However, when expressed as a percentage of mass, the proportion of calcium in relation to other exoskeletal components stays fairly constant throughout larval development. The only other study to investigate calcification in larval lobsters was completed by Spicer and Eriksson (2003), on the Norway lobster *Nephrops norvegicus*. However, only Zoea III was examined and while *N. norvegicus* Zoea III had $1.7 \text{ Ca } \mu\text{g mm}^{-2}$ (4.3% of mass), *H. gammarus* Zoea III values, in term of calcium concentration per surface area, were much lower than those found in *N. norvegicus*.

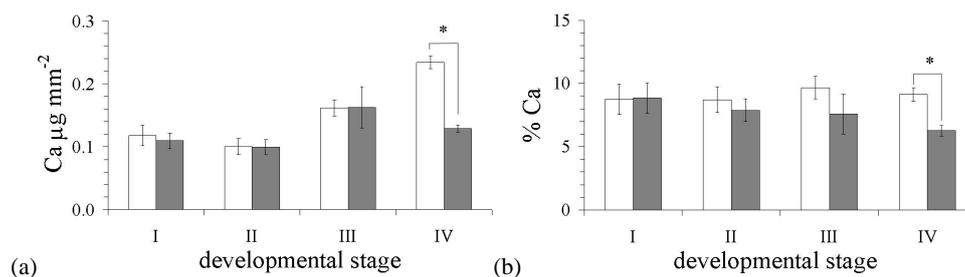


Fig. 3. Changes in the calcium concentration of the carapace during development and exposure to CO₂-acidification (1200 ppm), expressed as (a) concentration per surface area and (b) % carapace dry mass. Values are means \pm 1 standard error; white bar, control; grey bar, 1200 ppm of CO₂. Asterisk denotes significant differences from control ($p < 0.05$).

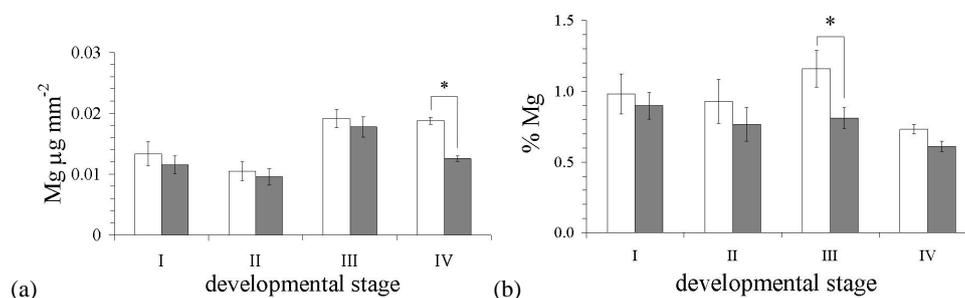


Fig. 4. Changes in the magnesium concentration of the carapace during development and exposure to CO₂-acidification (1200 ppm), expressed as (a) concentration per surface area and (b) % carapace dry mass. Values are means \pm 1 standard error; white bar, control; grey bar, 1200 ppm of CO₂. Asterisk denotes significant differences from control ($p < 0.05$).

However, the percentage of calcium in relation to mass was double the value in *H. gammarus* compared to *N. norvegicus*, indicating that the processes involved in calcification may be reasonably different between the two species. Magnesium concentrations were also measured and similarly displayed an increase with development; although the ratios of calcium to magnesium can be variable in many marine calcifying species (Boßelmann et al., 2007). It is hypothesised that in crustaceans, magnesium is often used as a substitute for calcium in the mineral matrix of the exoskeleton (Richards, 1951). However, when the percentage of calcium increased at Zoea IV the percentage of magnesium decreased, possibly showing that calcium plays a more important role during the final stages of development in *H. gammarus*.

4.2 Impacts of elevated CO₂ on growth and carapace mineralogy

This is also the first study to examine the effects of CO₂-induced acidification on growth and net carapace divalent ion concentration (as a measure of calcification; Findlay et al., 2009) of any lobster species. In the field increased moult frequency and high rates of mortality are associated with larval development; therefore these early stages may be particularly vulnerable to ocean acidification due to an increased energy requirement for calcification of the exoskeleton (Hau-

gan et al., 2006). Carapace length in *H. gammarus* was not significantly affected by culture in CO₂-acidified sea water (1200 ppm CO₂), with all remaining coupled throughout. However, both carapace mass and calcification were considerably reduced during metamorphosis into Zoea IV due to increased CO₂. The fact that carapace length was not affected by culture in CO₂-acidified sea water even though both mass and mineral content did appear to decrease, is feasible because Spicer and Eriksson (2003) indicates that the majority of growth occurs through laying down organic material and chitin and not CaCO₃. The reduced carapace mass observed was therefore most likely due to CO₂-induced acidification resulting in a decline in the net production of CaCO₃, which would potentially result in a lighter carapace.

It is thought that lobsters utilize HCO₃⁻ or CO₂ for the precipitation of CaCO₃ (Cameron, 1989) not CO₃²⁻ therefore if the experimental conditions had resulted in undersaturation with respect to carbonate minerals, we still might not expect a direct impact on calcification in larval lobsters. However, the sea water in both the control and the elevated CO₂ treatment had relatively high levels of CO₃²⁻, and neither became low enough to result in undersaturation with respect to any of the calcium carbonate polymorphs relevant here ($\Omega_{\text{aragonite}} > 2.5$; Table 1). This seems to occur as a result of naturally high alkalinity levels in the sea water ($> 2450 \mu\text{Eq kg}^{-1}$), and indicates that neither CO₃²⁻ or

Table 1. System data (mean±standard error) for the control and the high CO₂ treatment. Salinity, temperature, pH and *p*CO₂ were measured; all other data (DIC=dissolved inorganic carbon, *A_T*=total alkalinity; CO₃²⁻=carbonate ion concentration; Ω_{calcite}=calcite saturation state; Ω_{aragonite}=aragonite saturation state) were calculated from pH and *p*CO₂ using CO₂sys (Pierrot et al., 2006), with dissociation constants from Mehrbach et al. (1973) refit by Dickson and Millero (1987) and KSO₄ using Dickson (1990).

	Control	High CO ₂ Treatment
CO ₂ (ppm)	315±18.83	1202±29.83
pH	8.39±0.006	8.10±0.009
Temp (°C)	17.0±1.0	17.0±1.0
Sal (psu)	35.0±1.0	35.0±1.0
<i>A_T</i> (μEq kg ⁻¹)	2544±148.9	4290±145.9
DIC (μmol kg ⁻¹)	2152±131.1	3967±132.8
Ω _{calcite}	6.71±0.43	6.79±0.32
Ω _{aragonite}	4.33±0.28	4.38±0.20
HCO ₃ ⁻ (μmol kg ⁻¹)	1863±112.9	3651±119.5
CO ₃ ²⁻ (μmol kg ⁻¹)	281±18.1	285±13.3

HCO₃⁻ were limiting calcification, nor was there any indication of enhanced dissolution. One caution to these results is that pH and *p*CO₂ were measured during the experiment but total alkalinity and DIC were calculated using CO₂sys (Pierrot et al., 2006), with dissociation constants from Mehrbach et al. (1973) refit by Dickson and Millero (1987) and KSO₄ using Dickson (1990), and therefore these may not represent exact values, particularly as the sea water comes from a coastal environment. The increased CO₂, added through gas bubbling, increased the total dissolved inorganic carbon, and hence lowered the pH, although not below levels perceived to be “normal”. Therefore the observed impacts on mass and reduced calcium concentration in these larval *H. gammarus* may primarily be the result of hypercapnia interfering with normal homeostatic function (perhaps *via* a trade-off), and not a direct impact on calcification *per se*, e.g. general physiological stress can result in a reduction in the energy allocated to shell thickening (Henry et al., 1981). A similar study by Gazeau et al. (2007), using comparable CO₂ values, also displayed a net decline in the calcium carbonate structure in the mussel, *Mytilus edulis*, and the Pacific oyster, *Crassostrea gigas*. As in this study, they too found that calcium carbonate polymorphs did not become undersaturated, but did suggest that saturation states were correlated with net calcification rates. Here we suggest that saturation states may not always be the main limiting factor for calcification under increasing CO₂, as the processes and mechanisms for calcification in multi-cellular organisms are complex and are closely linked with many other physiological processes (Pörtner, 2008). As the solubility of a calcite structure increases with the incorporation of magnesium, un-

der increasing CO₂ concentrations (Raven et al., 2005), several species have the ability to secrete a lower concentration of magnesium in response to environmental changes (Stanley et al., 2002). However, as the decrease in magnesium ions was fairly consistent with the decrease in calcium ions it seems unlikely that this mechanism for dealing with an altered environment was occurring in the present study.

CO₂-induced acidification displayed a progressive long-term CO₂ effect on the calcified exoskeleton in Zoea IV, which is arguably the most critical period for production of viable post-larvae. There has been no examination of the effects of OA on post-larval lobsters completed to date. As OA is predicted to occur over ocean surface waters, with a great degree of certainty, and corrosive waters are already seasonally observed in shelf sea upwelling areas (Feely et al., 2008) and around major rivers (Salisbury et al., 2008), marine organisms inhabiting the pelagic zone will be unable to avoid these unfavourable changes in ocean chemistry (Haugan, 1997).

From most studies on marine organisms to date there appears to be a substantial cost involved with increased CO₂ on developmental processes, whether it be decreased calcification or shell dissolution in order to maintain internal chemistry (Gazeau et al., 2007; Michaelidis et al., 2005), or increase muscle wastage in order to maintain skeletal integrity (Wood et al., 2008). A net decline in calcification, along with a reduced shell mass of developing larval lobsters may affect their competitive fitness and recruitment success; this could trigger cascading trophic effects on population dynamics and potentially on the functioning of marine ecosystems. It is not certain whether the adverse effects associated with OA may be counteracted by physiological acclimatization and/or genetic adaptation of marine organisms (Riebesell, 2004). However initial findings do not appear promising and assessments of potential impacts are hampered by the scarcity of relevant research (Orr et al., 2005).

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References

- Aiken, D. E.: Proecdysis, setal development, and molt prediction in the American lobster (*Homarus americanus*), J. Fish. Res. Bd. Can., 30, 1337–1344, 1973.
- Barry, J. P., Buck, K. R., Lovera, C., Kuhnz, L., and Whaling, P. J.: Utility of deep sea CO₂ release experiments in understanding the biology of a high-CO₂ ocean: effects of hyper-

- capnia on deep sea meiofauna, *J. Geophys. Res.*, 110, C09S12, doi:10.1029/2004JC002629, 2005.
- Bibby, R., Cleall-Harding, P., Rundle, S. D., Widdicombe, S., and Spicer J. I.: Ocean acidification induced defenses in the intertidal gastropod *Littorina littorea*, *Biol. Lett.*, 3, 699–701, 2007.
- Bibby, R., Widdicombe, S., Parry, H., Spicer, J., and Pipe, R.: Effects of ocean acidification on the immune response of the blue mussel *Mytilus edulis*, *Aquat. Biol.*, 2, 67–74, 2008.
- BoBelmann, F., Romano, P., Fabritius, H., Raabe, D. and Epple, M.: The composition of the exoskeleton of two Crustacea: the American lobster *Homarus americanus* and the edible crab *Cancer pagurus*, *Thermochemica Acta*, 463, 65–68, 2007.
- Caldeira, K. and Wickett, M. E.: Anthropogenic carbon and ocean pH, *Nature*, 425, p. 365, 2003.
- Cameron, J. N.: Acid-base homeostasis: past and present perspectives, *Physiol. Zool.*, 62, 845–865, 1989.
- Carlberg, J. M. and Van Olst, J. C.: Brine shrimp (*Artemia salina*) consumption by the larval stages of the American lobster (*Homarus americanus*) in relation to food density and water temperature, *Proceedings of the Annual Meeting – World Mariculture Society*, 7, 379–389, 1976.
- Chang, E. S., Chang, S. A., and Mulder, E. P.: Hormones in the lives of crustaceans: an overview, *Am. Zool.*, 41, 1090–1097, 2001.
- Dupont, S., Havenhand, J., Thorndyke, W., Peck, L., and Thorndyke, M.: Near-future level of CO₂ – driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*, *Mar. Ecol. Prog. Ser.*, 373, 285–294, 2008.
- Egilsdottir, H., Spicer, J. I., and Rundle, S. D.: The effect of CO₂ acidified sea water and reduced salinity on aspects of the embryonic development of the amphipod, *Echinogammarus marinus* (Leach), *Mar. Poll. Bull.*, 8, 1187–1191, 2009.
- Ellis, R. P., Bersey, J., Rundle, S. D., Hall-Spencer, J. M., and Spicer, J. I.: Subtle but significant effects of CO₂ acidified sea water on embryos of the intertidal snail *Littorina obtusata*, *Aquat. Biol.*, 5, 41–48, 2009.
- Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J., and Millero, F. J.: Impact of anthropogenic CO₂ on the CaCO₃ system in the ocean, *Science*, 305, 362–366, 2004.
- Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., and Hales, B.: Evidence for upwelling of corrosive “acidified” water onto the continental shelf, *Science*, 320, 1490–1492, 2008.
- Findlay, H. S., Kendall, M. A., Spicer, J. I., and Widdicombe, S.: Future high CO₂ in the intertidal may compromise adult barnacle (*Semibalanus balanoides*) survival and embryo development rate, *Mar. Ecol. Prog. Ser.*, in press, 2009.
- Findlay, H. S., Wood, H. L., Kendall, M. A., Spicer, J. I., Twitchett, R. A., and Widdicombe, S.: Comparing the impact of high CO₂ on calcium carbonate structures in different marine organisms, *J. Exp. Mar. Biol. Ecol.*, in review, 2009.
- Findlay, H. S., Kendall, M. A., Spicer, J. I., Turley, C., and Widdicombe, S.: A novel microcosm system for investigating the impacts of elevated carbon dioxide and temperature on intertidal organisms, *Aquat. Biol.*, 3, 51–62, 2008.
- Gazeau, F., Quiblier, C., Jansen, J. M., and Gattuso, J. P.: Mid-delburg, J. J. and Heip, C. H. R.: Impact of elevated CO₂ on shellfish calcification, *Geophys. Res. Lett.*, 34, L07603, doi:10.1029/2006GL028554, 2007.
- Haugan, P. M.: Impacts on the marine environment from direct and indirect ocean storage of CO₂, *Waste Manage.*, 17, 323–327, 1997.
- Haugan, P. M., Turley, C., and Pörtner, H.-O.: Effects on the marine environment of ocean acidification resulting from elevated levels of CO₂ in the atmosphere, Document prepared by an intercessional working group convened by Norway and the United Kingdom, Report to the OSPAR commission, 1, 1–27, 2006.
- Havenhand J., Buttler, F.-R., Thorndyke M. C., and Williamson, J. E.: Near-future levels of ocean acidification reduce fertilization success in a sea urchin, *Curr. Biol.*, 18, R651–R652, 2008.
- Henry, R. P., Kormanik, G. A., Smartresk, N. J., and Cameron, J. N.: The role of CaCO₃ dissolution as a source of HCO₃⁻ for the buffering of hypercapnic acidosis in aquatic and terrestrial decapod crustaceans, *J. Exp. Biol.*, 94, 269–274, 1981.
- Hinga, K. R.: Effects of pH on coastal phytoplankton, *Mar. Ecol. Prog. Ser.*, 238, 281–300, 2002.
- Holman, J. D., Burnett, K. G., and Burnett L. E.: Effects of hypercapnic hypoxia on the clearance of *Vibrio campbellii* in the blue crab, *Callinectes sapidus*, *Biol. Bull. Mar. Biol. Lab. Mass.*, 206, 188–196, 2004.
- IPCC: The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) Cambridge University Press: Cambridge, UK, and New York, USA, 2007.
- Ishimatsu, A., Kikkawa, T., Hayashi, M., Lee, K. S., and Kita, J.: Effects of CO₂ on marine fish: larvae and adults, *J. Oceanogr.*, 60, 731–741, 2004.
- Kikkawa, T., Ishimatsu, A., and Kita, J.: Acute CO₂ tolerance during the early developmental stages of four marine teleosts, *Environ. Toxicol.*, 18, 375–382, 2003.
- Kleypas, J. A., Feely, R. A., Fabry, V. J., Langdon, C. Sabine, C. L., and Robbins, L. L.: Impacts of ocean acidification on coral reefs and other marine calcifiers: a guide for future research, report of a workshop held 18–20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey, 2006.
- Kurihara, H., Shimode, S., and Shirayama, Y.: Sub-lethal effects of elevated concentration of CO₂ on planktonic copepods and sea urchins, *J. Oceanogr.*, 60, 743–750, 2004a.
- Kurihara, H., Shimode, S., and Shirayama, Y.: Effects of raised CO₂ concentration on the egg production rate and early development of two marine copepods (*Arctia steuri* and *Acartia erythraea*), *Mar. Pollut. Bull.*, 49, 721–727, 2004b.
- Kurihara, H. and Shirayama, Y.: Effects of increased atmospheric CO₂ on sea urchin early development, *Mar. Ecol. Prog. Ser.*, 274, 161–169, 2004.
- Langdon, C. and Atkinson, M. J.: Effect of elevated pCO₂ on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment, *J. Geophys. Res.*, 110, C09S07, doi:10.1029/2004JC002576, 2005.
- Langenbuch, M. and Pörtner, H.-O.: Changes in metabolic rate and N excretion in the marine invertebrate *Sipunculus nudus* under conditions of environmental hypercapnia: identifying effective acid–base variables, *J. Exp. Biol.*, 205, 1153–1160, 2002.
- Michaelidis, B., Ouzounis, C., Pleras, A., and Pörtner, H.-O.: Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels (*Mytilus galloprovincialis*), *Mar. Ecol. Prog. Ser.*, 293, 109–118, 2005.
- Morse, J. W., Andersson, A. J., and Mackenzie, F. T.: Initial responses of carbonate-rich shelf sediments to rising atmospheric

- $p\text{CO}_2$ and “Ocean acidification”: Role of high Mg-calcites, *Geochim. Cosmochim. Ac.*, 70, 5814–5830, 2006.
- Neufeld, D. S. and Cameron, J. N.: Postmoult uptake of calcium by the blue crab (*Callinectes sapidus*) in water of low salinity, *J. Exp. Biol.*, 171, 283–299, 1992.
- Orr, J. C., Fabry, V. J., Aumont, O., et al.: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, 437, 681–686, 2005.
- Paasche, E.: A review of the coccolithophorid *Emiliania huxleyi* (Prymnesiophyceae), with particular reference to growth, coccolith formation, and calcification photosynthesis interactions, *Phycologia*, 40, 503–529, 2001.
- Pörtner, H.-O., Langenbuch, M., and Reipschläger, A.: Biological impact of elevated ocean CO_2 concentrations: lessons from animal physiology and Earth history, *J. Oceanogr.*, 60, 705–718, 2004.
- Pörtner, H.-O., Langenbuch, M., and Michaelidis, B.: Synergistic effects of temperature extremes, hypoxia, and increases in CO_2 on marine animals: From Earth history to global change, *J. Geophys. Res.*, 110, C09S10, doi:10.1029/2004JC002561, 2005.
- Pörtner, H.-O.: Ecosystem effects of ocean acidification in times of ocean warming: a physiologist’s view, *Mar. Ecol. Prog. Ser.*, 373, 203–217, 2008.
- Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., and Watson, A.: Ocean acidification due to increasing atmospheric carbon dioxide, Policy document 12/05, online available at: www.royalsoc.ac.uk, The Royal Society, UK, 2005.
- Reynaud, S., Leclercq, N., Romaine-Lioud, S., Ferrier-Pagés, C., Jaubert, J., and Gattuso, J. P.: Interacting effects of CO_2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral, *Glob. Change Biol.*, 9, 1660–1668, 2003.
- Richards, A. G.: The integument of arthropods. University of Minnesota Press, Minneapolis, 1951.
- Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R., and Morel, F. M. M.: Reduced calcification of marine plankton in response to increased atmospheric CO_2 , *Nature*, 407, 364–367, 2000.
- Riebesell, U.: Effects of CO_2 enrichment on marine phytoplankton, *J. Oceanogr.*, 60, 719–729, 2004.
- Sabine, C. L., Feely, R. A., Gruber, N., et al.: The oceanic sink for anthropogenic CO_2 , *Science*, 305, 367–371, 2004.
- Salisbury, J., Green, M., Hunt, C., and Campbell, J.: Coastal acidification by rivers: A new threat to shellfish? *Eos, Transactions, American Geophysical Union*, 89(50), 513–513, 2008.
- Shirayama, Y. and Thornton, H.: Effect of increased atmospheric CO_2 on shallow water marine benthos, *J. Geophys. Res.*, 110(C9), C09S08, doi:10.1029/2004JC002618, 2005.
- Stanley, S. M., Ries, J. B., and Hardie, L. A.: Low magnesium calcite produced by coralline algae in seawater of Late Cretaceous composition, *P. Natl. Acad. Sci. USA*, 99, 15323–15326, 2002.
- Spicer, J. I. and Eriksson, S. P.: Does the development of respiratory regulation always accompany the transition from pelagic larvae to benthic fossorial postlarvae in the Norway lobster *Nephrops norvegicus* (L.)?, *J. Exp. Mar. Biol. Ecol.*, 295, 219–243, 2003.
- Spicer, J. I., Raffo, A., and Widdicombe, S.: Influence of CO_2 -related seawater acidification on extracellular acid-base balance in the velvet swimming crab *Necora puber*, *Mar. Biol. (Berl.)*, 151, 1117–1125, 2007.
- Wickins, J. F.: The effect of reduced pH on carapace calcium, strontium and magnesium levels in rapidly growing prawns (*Penaeus monodon* Fabricius), *Aquaculture*, 41, 49–60, 1984.
- Widdicombe, S. and Spicer, J. I.: Predicting the impact of ocean acidification on benthic biodiversity: What can animal physiology tell us?, *J. Exp. Mar. Biol. Ecol.*, 366, 187–197, 2008.
- Wood, H. L., Spicer, J. I., and Widdicombe, S.: Ocean acidification may increase calcification rates, but at a cost, *P. Roy. Soc., Lond.*, 275B, 1767–1773, 2008.
- Zondervan, I., Rost, B., and Riebesell, U.: Effect of CO_2 concentration on the PIC/POC ratio in the coccolithophore *Emiliania huxleyi* grown under light-limiting conditions and different day lengths, *J. Exp. Mar. Biol. Ecol.*, 272, 55–70, 2002.