

In this review:

- A. Recent articles – no abstract
- B. Recent articles with abstracts

O/A denotes an open access article or journal

A. Recent articles – no abstract

Turley, C., Eby, M., Ridgwell, A.J., Schmidt, D.N., Findlay, H.S., Brownlee, C., Riebesell, U., Fabry, V.J., Feely, R.A., and Gattuso, J.P. **The societal challenge of ocean acidification.** *Marine Pollution Bulletin* 60(6): 787-792, 2010.

Kerr, R.A. **Ocean acidification unprecedented, unsettling.** *Science* 328(5985): 1500-1501, 2010.

Hardt, M.J. and Safina, C. **Threatening ocean life from the inside.** *Scientific American* 303(2): 66-73, 2010.

B. Recent articles with abstracts

Dias, B.B., Hart, M.B., Smart, C.W., and Hall-Spencer, J.M. **Modern seawater acidification: the response of foraminifera to high-CO₂ conditions in the Mediterranean Sea.** *Journal of the Geological Society* 167(5): 843-846, 2010.

Notes: The seas around the island of Ischia (Italy) have a lowered pH as a result of volcanic gas vents that emit carbon dioxide from the sea floor at ambient seawater temperatures. These areas of acidified seawater provide natural laboratories in which to study the long-term biological response to rising CO₂ levels. Benthic foraminifera (single-celled protists) are particularly interesting as they have short life histories, are environmentally sensitive and have an excellent fossil record. Here, we examine changes in foraminiferal assemblages along pH gradients at CO₂ vents on the coast of Ischia and show that the foraminiferal distribution, diversity and nature of the fauna change markedly in the living assemblages as pH decreases.

Lannig, G., Eilers, S., Pörtner, H.O., Sokolova, I.M., and Bock, C. **Impact of ocean acidification on energy metabolism of oyster, *Crassostrea gigas* – changes in metabolic pathways and thermal response.** *Marine Drugs* 8(8): 2318-2339, 2010.

O/A

Notes: Climate change with increasing temperature and ocean acidification (OA) poses risks for marine ecosystems. According to Pörtner and Farrell, synergistic effects of elevated temperature and CO₂-induced OA on energy metabolism will narrow the thermal tolerance window of marine ectothermal animals. To test this hypothesis, we investigated the effect of an acute temperature rise on energy metabolism of the oyster, *Crassostrea gigas* chronically exposed to elevated CO₂ levels (partial pressure of CO₂ in the seawater ~0.15 kPa, seawater pH ~ 7.7). Within one month of incubation at elevated P_{CO₂} and 15 °C hemolymph pH fell (pH_e = 7.1 ± 0.2 (CO₂-group) *vs.* 7.6 ± 0.1 (control)) and P_eCO₂ values in hemolymph increased (0.5 ± 0.2 kPa (CO₂-group) *vs.* 0.2 ± 0.04 kPa (control)). Slightly but significantly elevated bicarbonate concentrations in the hemolymph of CO₂-incubated oysters ([HCO₃⁻]_e = 1.8 ± 0.3 mM (CO₂-group) *vs.* 1.3 ± 0.1 mM (control)) indicate only minimal regulation

of extracellular acid-base status. At the acclimation temperature of 15 °C the OA-induced decrease in pH_e did not lead to metabolic depression in oysters as standard metabolism rates (SMR) of CO_2 -exposed oysters were similar to controls. Upon acute warming SMR rose in both groups, but displayed a stronger increase in the CO_2 -incubated group. Investigation in isolated gill cells revealed a similar temperature-dependence of respiration between groups. Furthermore, the fraction of cellular energy demand for ion regulation via Na^+/K^+ -ATPase was not affected by chronic hypercapnia or temperature. Metabolic profiling using ^1H -NMR spectroscopy revealed substantial changes in some tissues following OA exposure at 15 °C. In mantle tissue alanine and ATP levels decreased significantly whereas an increase in succinate levels was observed in gill tissue. These findings suggest shifts in metabolic pathways following OA-exposure. Our study confirms that OA affects energy metabolism in oysters and suggests that climate change may affect populations of sessile coastal invertebrates such as mollusks.

Winans, A.K. and Purcell, J.E. **Effects of pH on asexual reproduction and statolith formation of the scyphozoan, *Aurelia labiata*.** *Hydrobiologia* 645(1): 39-52, 2010.

Notes: Although anthropogenic influences such as global warming, overfishing, and eutrophication may contribute to jellyfish blooms, little is known about the effects of ocean acidification on jellyfish. Most medusae form statoliths of calcium sulfate hemihydrate that are components of their balance organs (statocysts). This study was designed to test the effects of pH (7.9, within the average current range, 7.5, expected by 2100, and 7.2, expected by 2300) combined with two temperatures (9 and 15 °C) on asexual reproduction and statolith formation of the moon jellyfish, *Aurelia labiata*. Polyp survival was 100% after 122 d in seawater in all six temperature and pH combinations. Because few polyps at 9 °C strobilated, and temperature effects on budding were consistent with published results, we did not analyze data from those three treatments further. At 15 °C, there were no significant effects of pH on the numbers of ephyrae or buds produced per polyp or on the numbers of statoliths per statocyst; however, statolith size was significantly smaller in ephyrae released from polyps reared at low pH. Our results indicate that *A. labiata* polyps are quite tolerant of low pH, surviving and reproducing asexually even at the lowest tested pH; however, the effects of small statoliths on ephyra fitness are unknown. Future research on the behavior of ephyrae with small statoliths would further our understanding of how ocean acidification may affect jellyfish survival in nature.

Pelejero, C., Calvo, E., and Hoegh-Guldberg, O. **Paleo-perspectives on ocean acidification.** *Trends in Ecology and Evolution* 25(6): 332-344, 2010.

Notes: The anthropogenic rise in atmospheric CO_2 is driving fundamental and unprecedented changes in the chemistry of the oceans. This has led to changes in the physiology of a wide variety of marine organisms and, consequently, the ecology of the ocean. This review explores recent advances in our understanding of ocean acidification with a particular emphasis on past changes to ocean chemistry and what they can tell us about present and future changes. We argue that ocean conditions are already more extreme than those experienced by marine organisms and ecosystems for millions of years, emphasising the urgent need to adopt policies that drastically reduce CO_2 emissions.

Nienhuis, S., Palmer, A.R., and Harley, C.D.G. **Elevated CO_2 affects shell dissolution rate but not calcification rate in a marine snail.** *Proceedings of the Royal Society of London [B]* 277(1693): 2553-2558, 2010.

Notes: As CO_2 levels increase in the atmosphere, so too do they in the sea. Although direct effects of moderately elevated CO_2 in sea water may be of little consequence, indirect effects may be profound. For example, lowered pH and calcium carbonate saturation states may influence both deposition and dissolution rates of mineralized skeletons in many marine organisms. The relative impact of elevated CO_2 on deposition and dissolution rates are not known for many large-bodied organisms. We therefore tested the effects of increased CO_2 levels—those forecast to occur in roughly 100 and 200 years—on both shell deposition rate and shell dissolution rate in a rocky intertidal snail, *Nucella lamellosa*. Shell weight gain per day in live snails decreased linearly with increasing CO_2 levels. However, this trend was paralleled by shell weight loss per day in empty shells, suggesting that these declines in shell weight gain observed in live snails were due to increased dissolution of existing shell material, rather than reduced production of new shell material. Ocean acidification may therefore have a greater effect on shell dissolution than on shell deposition, at least in temperate marine molluscs.

Gutowska, M.A., Melzner, F., Pörtner, H.O., and Meier, S. **Cuttlebone calcification increases during exposure to elevated seawater $p\text{CO}_2$ in the cephalopod *Sepia officinalis*.** *Marine Biology* 157(7): 1653-1663, 2010.

Notes: Changes in seawater carbonate chemistry that accompany ongoing ocean acidification have been found to affect calcification processes in many marine invertebrates. In contrast to the response of most invertebrates, calcification rates increase in the cephalopod *Sepia officinalis* during long-term exposure to elevated seawater $p\text{CO}_2$. The present trial investigated structural changes in the cuttlebones of *S. officinalis* calcified during 6 weeks of exposure to 615 Pa CO_2 . Cuttlebone mass increased sevenfold over the course of the growth trial, reaching a mean value of 0.71 ± 0.15 g. Depending on cuttlefish size (mantle lengths 44-56 mm), cuttlebones of CO_2 -incubated individuals accreted 22-55% more CaCO_3 compared to controls at 64 Pa CO_2 . However, the height of the CO_2 -exposed cuttlebones was reduced. A decrease in spacing of the cuttlebone lamellae, from 384 ± 26 to 195 ± 38 μm , accounted for the height reduction. The greater CaCO_3 content of the CO_2 -incubated cuttlebones can be attributed to an increase in thickness of the lamellar and pillar walls. Particularly, pillar thickness increased from 2.6 ± 0.6 to 4.9 ± 2.2 μm . Interestingly, the incorporation of non-acid-soluble organic matrix (chitin) in the cuttlebones of CO_2 -exposed individuals was reduced by 30% on average. The apparent robustness of calcification processes in *S. officinalis*, and other powerful ion regulators such as decapod crustaceans, during exposure to elevated $p\text{CO}_2$ is predicated to be closely connected to the increased extracellular $[\text{HCO}_3^-]$ maintained by these organisms to compensate extracellular pH. The potential negative impact of increased calcification in the cuttlebone of *S. officinalis* is discussed with regard to its function as a lightweight and highly porous buoyancy regulation device. Further studies working with lower seawater $p\text{CO}_2$ values are necessary to evaluate if the observed phenomenon is of ecological relevance.

Anderson, L.G., Tanhua, T., Bjork, G., Hjalmarrsson, S., Jones, E.P., Jutterstrom, S., Rudels, B., Swift, J.H., and Wahlstrom, I. **Arctic ocean shelf-basin interaction: An active continental shelf CO_2 pump and its impact on the degree of calcium carbonate solubility.** *Deep Sea Research Part I: Oceanographic Research Papers* 57(7): 869-879, 2010.

Notes: The Arctic Ocean has wide shelf areas with extensive biological activity including a high primary productivity and an active microbial loop within the surface sediment. This in combination with brine production during sea ice formation result in the decay products exiting from the shelf into the deep basin typically at a depth of about 150 m and over a wide salinity range centered around $S \sim 33$. We present data from the Beringia cruise in 2005 along a section in the Canada Basin from the continental margin north of Alaska towards the north and from the International Siberian Shelf Study in 2008 (ISSS-08) to illustrate the impact of these processes. The water rich in decay products, nutrients and dissolved inorganic carbon (DIC), exits the shelf not only from the Chukchi Sea, as has been shown earlier, but also from the East Siberian Sea. The excess of DIC found in the Canada Basin in a depth range of about 50-250 m amounts to 90 ± 40 g C m^{-2} . If this excess is integrated over the whole Canadian Basin the excess equals $320 \pm 140 \times 10^{12}$ g C. The high DIC concentration layer also has low pH and consequently a low degree of calcium carbonate saturation, with minimum aragonite values of 60% saturation and calcite values just below saturation. The mean age of the waters in the top 300 m was calculated using the transit time distribution method. By applying a future exponential increase of atmospheric CO_2 the invasion of anthropogenic carbon into these waters will result in an under-saturated surface water with respect to aragonite by the year 2050, even without any freshening caused by melting sea ice or increased river discharge.

Feely, R.A., Alin, S.R., Newton, J., Sabine, C.L., Warner, M., Devol, A., Krembs, C., and Maloy, C. **The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary.** *Estuarine, Coastal and Shelf Science* 88(4): 442-449, 2010.

Notes: Puget Sound is a large estuary complex in the U.S. Pacific Northwest that is home to a diverse and economically important ecosystem threatened by anthropogenic impacts associated with climate change, urbanization, and ocean acidification. While ocean acidification has been studied in oceanic waters, little is known regarding its status in estuaries. Anthropogenically acidified coastal waters upwelling along the western North American continental margin can enter Puget Sound through the Strait of Juan de Fuca. In order to study the combined effects of ocean acidification and other natural and anthropogenic processes on Puget Sound waters, we made the first inorganic carbon measurements in this estuary on two survey cruises in February and August of 2008. Observed pH and aragonite saturation state values in surface and subsurface waters were substantially lower in parts of Puget Sound than would be expected from anthropogenic carbon dioxide (CO_2)

uptake alone. We estimate that ocean acidification can account for 24-49% of the pH decrease in the deep waters of the Hood Canal sub-basin of Puget Sound relative to estimated pre-industrial values. The remaining change in pH between when seawater enters the sound and when it reaches this deep basin results from remineralization of organic matter due to natural or anthropogenically stimulated respiration processes within Puget Sound. Over time, however, the relative impact of ocean acidification could increase significantly, accounting for 49-82% of the pH decrease in subsurface waters for a doubling of atmospheric CO₂. These changes may have profound impacts on the Puget Sound ecosystem over the next several decades. These estimates suggest that the role ocean acidification will play in estuaries may be different from the open ocean.

Yamada, N., Tsurushima, N., and Suzumura, M. **Effects of seawater acidification by ocean CO₂ sequestration on bathypelagic prokaryote activities.** *Journal of Oceanography* 66(4): 571-580, 2010.

Notes: We investigated the effects of seawater acidification induced by ocean CO₂ sequestration on bathypelagic prokaryotes. We simulated acidification conditions by bubbling high-CO₂ air or adding chemical buffer solutions to seawater samples in order to examine changes in total cell counts, heterotrophic production rate, direct viable cell count, and relative abundance of Bacteria and Archaea. Considerable suppression of prokaryotic activities was observed at pH 7.0 or lower, especially in samples enriched with organic matter. The relative abundance of Archaea increased with increasing CO₂ concentration. We found that seawater acidification can potentially alter heterotrophic activities and community structure of bathypelagic prokaryotes.

Nielsen, L.T., Jakobsen, H.H., and Hansen, P.J. **High resilience of two coastal plankton communities to twenty-first century seawater acidification: Evidence from microcosm studies.** *Marine Biology Research* 6(6): 542-555, 2010.

Notes: Increased free CO₂ and ocean acidification are among the consequences of anthropogenic carbon emissions. Responses of marine protists to increased levels of CO₂ are highly species-specific, and this has been suggested to cause an alteration in plankton species composition, community functions and ultimately biogeochemical cycles. This study aims to test this by performing microcosm incubation experiments at present (pH 8.0) and at three lowered pH levels (pH 7.8, 7.6 and 6.0), corresponding to free CO₂ concentrations of 24, 38, 58 & 610 μmol l⁻¹, respectively. Results from two such experiments are reported, and measurements include microscopy counts of ~20 planktonic protist taxa, HPLC pigment analysis, FlowCAM analysis of cell-size spectra, photosynthetic activity and total POC and PON. Initial communities were flagellate (experiment 1) and dinoflagellate and ciliate (experiment 2) dominated, but at pH 8.0, 7.8 and 7.6 a diatom dominance developed during the first days in both experiments. Profound changes in all measured parameters were found as a result of the pH 6.0 treatment, but among the other three pH treatments significant differences were few; *Karlodinium* spp. was the only taxon to be affected significantly, and plankton group composition, cell sizes and photosynthetic activity all remained unaffected during the 14-day incubation periods. Thus, both of the investigated coastal plankton communities were unaffected by twenty-first century expected changes in pH and free CO₂. This may be explained by the large seasonal, and even daily, changes in pH seen in productive marine ecosystems, and the corresponding need for algae to be pH-tolerant.

Zippay, M.L. and Hofmann, G.E. **Effect of pH on gene expression and thermal tolerance of early life history stages of red abalone (*Haliotis rufescens*).** *Journal of Shellfish Research* 29(2): 429-439, 2010.

Notes: A growing body of research on calcifying marine invertebrates suggests that ocean acidification will have deleterious effects on development and various physiological processes in these organisms. In laboratory experiments designed to mimic seawater chemistry in future oceans, we examined the effect of pH reduction, driven by the carbon dioxide (CO₂) acidification of seawater, on larvae of the red abalone, *Haliotis rufescens*. Following development under CO₂-acidified conditions, we measured 2 indicators of physiological response to low pH in 4 stages of larval development: (1) tolerance of acute thermal challenges and (2) quantitative real-time polymerase chain reaction-determined expression of 2 genes involved in shell formation (*engrailed* and *ap24*). The results showed that low pH (pH 7.87 vs. pH 8.05 for control treatments) had a significant effect and decreased larval thermal tolerance for some developmental stages (pretorsion and late veliger), but not for others (posttorsion and premetamorphic veligers). In contrast to the thermal tolerance data, decreased pH did not affect the

expression pattern of the 2 shell formation genes in any of the abalone larval stages. The results indicate larval stages were differentially sensitive to low pH conditions and this variability may play into the resilience of individual species to withstand environmental change in the longer term.

Lebrato, M., Iglesias-Rodríguez, D., Feely, R.A., Greeley, D., Jones, D.O.B., Suarez-Bosche, N., Lampitt, R.S., Cartes, J.E., Green, D.R.H., and Alker, B. **Global contribution of echinoderms to the marine carbon cycle: CaCO₃ budget and benthic compartments.** *Ecological Monographs* 80(3): 441-467, 2010. **O/A**

Notes: The contribution of carbonate-producing benthic organisms to the global marine carbon budget has been overlooked, the prevailing view being that calcium carbonate (CaCO₃) is predominantly produced and exported by marine plankton in the "biological pump." Here, we provide the first estimation of the global contribution of echinoderms to the marine inorganic and organic carbon cycle, based on organism-level measurements from species of the five echinoderm classes. Echinoderms' global CaCO₃ contribution amounts to ~0.861 Pg CaCO₃/yr (0.102 Pg C/yr of inorganic carbon) as a production rate, and ~2.11 Pg CaCO₃ (0.25 Pg C of inorganic carbon) as a standing stock from the shelves, slopes, and abyssal depths. Echinoderm inorganic carbon production (0.102 Pg C/yr) is less than the global pelagic production (0.4-1.8 Pg C/yr) and similar to the estimates for carbonate shelves globally (0.024-0.120 Pg C/yr). Echinoderm CaCO₃ production per unit area is ~27.01 g CaCO₃ m⁻² yr⁻¹ (3.24 g C m⁻² yr⁻¹ as inorganic carbon) on a global scale for all areas, with a standing stock of ~63.34 g CaCO₃/m² (7.60 g C/m² as inorganic carbon), and ~7.97 g C/m² as organic carbon. The shelf production alone is 77.91 g CaCO₃ m⁻² yr⁻¹ (9.35 g C m⁻² yr⁻¹ as inorganic carbon) in contrast to 2.05 g CaCO₃ m⁻² yr⁻¹ (0.24 g C m⁻² yr⁻¹ as inorganic carbon) for the slope on a global scale. The biogeography of the CaCO₃ standing stocks of echinoderms showed strong latitudinal variability. More than 80% of the global CaCO₃ production from echinoderms occurs between 0 and 800 m, with the highest contribution attributed to the shelf and upper slope. We provide a global distribution of echinoderm populations in the context of global calcite saturation horizons, since undersaturated waters with respect to mineral phases are surfacing. This shallowing is a direct consequence of ocean acidification, and in some places it may reach the shelf and upper slope permanently, where the highest CaCO₃ standing stocks from echinoderms originate. These organism-level data contribute substantially to the assessment of global carbonate inventories, which at present are poorly estimated. Additionally, it is desirable to include these benthic compartments in coupled global biogeochemical models representing the "biological pump" and its feedbacks, since at present all efforts have focused on pelagic processes, dominated by coccolithophores. The omission of the benthic processes from modeling will only diminish the understanding of elemental fluxes at large scales and any future prediction of climate change scenarios.

Erba, E., Bottini, C., Weissert, H.J., and Keller, C.E. **Calcareous nannoplankton response to surface-water acidification around Oceanic Anoxic Event 1a.** *Science* 329(5990): 428-432, 2010.

Notes: Ocean acidification induced by atmospheric CO₂ may be a major threat to marine ecosystems, particularly to calcareous nannoplankton. We show that, during the Aptian (~120 million years ago) Oceanic Anoxic Event 1a, which resulted from a massive addition of volcanic CO₂, the morphological features of calcareous nanofossils traced the biological response to acidified surface waters. We observe the demise of heavily calcified nannoconids and reduced calcite paleofluxes at the beginning of a pre-anoxia calcification crisis. Ephemeral coccolith dwarfism and malformation represent species-specific adjustments to survive lower pH, whereas later, abundance peaks indicate intermittent alkalinity recovery. Deepwater acidification occurred with a delay of 25,000 to 30,000 years. After the dissolution climax, nannoplankton and carbonate recovery developed over ~160,000 years under persisting global dysoxia-anoxia.

Rodolfo-Metalpa, R., Lombardi, C., Cocito, S., Hall-Spencer, J.M., and Gambi, M.C. **Effects of ocean acidification and high temperatures on the bryozoan *Myriapora truncata* at natural CO₂ vents.** *Marine Ecology: An Evolutionary Perspective* 31(3): 447-456, 2010.

Notes: There are serious concerns that ocean acidification will combine with the effects of global warming to cause major shifts in marine ecosystems, but there is a lack of field data on the combined ecological effects of these changes due to the difficulty of creating large-scale, long-term exposures to elevated CO₂ and temperature. Here we report the first coastal

transplant experiment designed to investigate the effects of naturally acidified seawater on the rates of net calcification and dissolution of the branched calcitic bryozoan *Myriapora truncata* (Pallas, 1766). Colonies were transplanted to normal (pH 8.1), high (mean pH 7.66, minimum value 7.33) and extremely high CO₂ conditions (mean pH 7.43, minimum value 6.83) at gas vents off Ischia Island (Tyrrhenian Sea, Italy). The net calcification rates of live colonies and the dissolution rates of dead colonies were estimated by weighing after 45 days (May-June 2008) and after 128 days (July-October) to examine the hypothesis that high CO₂ levels affect bryozoan growth and survival differently during moderate and warm water conditions. In the first observation period, seawater temperatures ranged from 19 to 24 °C; dead *M. truncata* colonies dissolved at high CO₂ levels (pH 7.66), whereas live specimens maintained the same net calcification rate as those growing at normal pH. In extremely high CO₂ conditions (mean pH 7.43), the live bryozoans calcified significantly less than those at normal pH. Therefore, established colonies of *M. truncata* seem well able to withstand the levels of ocean acidification predicted in the next 200 years, possibly because the soft tissues protect the skeleton from an external decrease in pH. However, during the second period of observation a prolonged period of high seawater temperatures (25-28 °C) halted calcification both in controls and at high CO₂, and all transplants died when high temperatures were combined with extremely high CO₂ levels. Clearly, attempts to predict the future response of organisms to ocean acidification need to consider the effects of concurrent changes such as the Mediterranean trend for increased summer temperatures in surface waters. Although *M. truncata* was resilient to short-term exposure to high levels of ocean acidification at normal temperatures, our field transplants showed that its ability to calcify at higher temperatures was compromised, adding it to the growing list of species now potentially threatened by global warming.

Small, D., Calosi, P., White, D., Spicer, J.I., and Widdicombe, S. **Impact of medium-term exposure to CO₂ enriched seawater on the physiological functions of the velvet swimming crab *Necora puber*.** *Aquatic Biology* 10(1): 11-21, 2010.

Notes: Ocean acidification (OA) is predicted to play a major role in shaping species biogeography and marine biodiversity over the next century. We tested the effect of medium-term exposure to OA (pH 8.00, 7.30 and 6.70 for 30 d) on acid-base balance in the decapod crab *Necora puber* – a species that is known to possess good extracellular buffering ability during short-term exposure to hypercapnic conditions. To determine if crabs undergo physiological trade-offs in order to buffer their haemolymph, we characterised a number of fundamental physiological functions, i.e. metabolic rate, tolerance to heat, carapace and chelae [Ca²⁺] and [Mg²⁺], haemolymph [Ca²⁺] and [Mg²⁺], and immune response in terms of lipid peroxidation. *Necora puber* was able to buffer changes to extracellular pH over 30 d exposure to hypercapnic water, with no evidence of net shell dissolution, thus demonstrating that HCO₃⁻ is actively taken up from the surrounding water. In addition, tolerance to heat, carapace mineralization, and aspects of immune response were not affected by hypercapnic conditions. In contrast, whole-animal O₂ uptake significantly decreased with hypercapnia, while significant increases in haemolymph [Ca²⁺] and [Mg²⁺] and chelae [Mg²⁺] were observed with hypercapnia. Our results confirm that most physiological functions in *N. puber* are resistant to low pH/hypercapnia over a longer period than previously investigated, although such resistance comes at the expenses of metabolic rates, haemolymph chemistry and chelae mineralization.

Hofmann, G.E., Barry, J.P., Edmunds, P.J., Gates, R.D., Hutchins, D.A., Klinger, T., and Sewell, M.A. **The effect of ocean acidification on calcifying organisms in marine ecosystems: An organism-to-ecosystem perspective.** *Annual Review of Ecology, Evolution, and Systematics* 41: 127-147, 2010.

Notes: Ocean acidification (OA), a consequence of anthropogenic carbon dioxide emissions, poses a serious threat to marine organisms in tropical, open-ocean, coastal, deep-sea, and high-latitude sea ecosystems. The diversity of taxonomic groups that precipitate calcium carbonate from seawater are at particularly high risk. Here we review the rapidly expanding literature concerning the biological and ecological impacts of OA on calcification, using a cross-scale, process-oriented approach. In comparison to calcification, we find that areas such as fertilization, early life-history stages, and interaction with synergistic stressors are understudied. Although understanding the long-term consequences of OA are critical, available studies are largely short-term experiments that do not allow for tests of long-term acclimatization or adaptation. Future research on the phenotypic plasticity of contemporary organisms and interpretations of performance in the context of current environmental heterogeneity of pCO₂ will greatly aid in our understanding of how organisms will respond to OA in the future.

De Bodt, C., Van Oostende, N., Harlay, J., Sabbe, K., and Chou, L. **Individual and interacting effects of $p\text{CO}_2$ and temperature on *Emiliania huxleyi* calcification: study of the calcite production, the coccolith morphology and the coccosphere size.** *Biogeosciences* 7(5): 1401-1412, 2010. **O/A**

Notes: The impact of ocean acidification and increased water temperature on marine ecosystems, in particular those involving calcifying organisms, has been gradually recognised. We examined the individual and combined effects of increased $p\text{CO}_2$ (180 ppmV CO_2 , 380 ppmV CO_2 and 750 ppmV CO_2 corresponding to past, present and future CO_2 conditions, respectively) and temperature (13 °C and 18 °C) during the exponential growth phase of the coccolithophore *E. huxleyi* using batch culture experiments. We showed that cellular production rate of Particulate Organic Carbon (POC) increased from the present to the future CO_2 treatments at 13 °C. A significant effect of $p\text{CO}_2$ and of temperature on calcification was found, manifesting itself in a lower cellular production rate of Particulate Inorganic Carbon (PIC) as well as a lower PIC:POC ratio at future CO_2 levels and at 18 °C. Coccosphere-sized particles showed a size reduction with both increasing temperature and CO_2 concentration. The influence of the different treatments on coccolith morphology was studied by categorizing SEM coccolith micrographs. The number of well-formed coccoliths decreased with increasing $p\text{CO}_2$ while temperature did not have a significant impact on coccolith morphology. No interacting effects of $p\text{CO}_2$ and temperature were observed on calcite production, coccolith morphology or on coccosphere size. Finally, our results suggest that ocean acidification might have a larger adverse impact on coccolithophorid calcification than surface water warming.

Gazeau, F., Gattuso, J.P., Dawber, C., Pronker, A.E., Peene, F., Peene, J., Heip, C.H.R., and Middelburg, J.J. **Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*.** *Biogeosciences* 7(7): 2051-2060, 2010. **O/A**

Notes: Several experiments have shown a decrease of growth and calcification of organisms at decreased pH levels. There is a growing interest to focus on early life stages that are believed to be more sensitive to environmental disturbances such as hypercapnia. Here, we present experimental data, acquired in a commercial hatchery, demonstrating that the growth of planktonic mussel (*Mytilus edulis*) larvae is significantly affected by a decrease of pH to a level expected for the end of the century. Even though there was no significant effect of a 0.25-0.34 pH unit decrease on hatching and mortality rates during the first 2 days of development nor during the following 13-day period prior to settlement, final shells were respectively 4.5 ± 1.3 and $6.0 \pm 2.3\%$ smaller at $\text{pH}_{\text{NBS}} \sim 7.8$ ($p\text{CO}_2 \sim 1100\text{-}1200 \mu\text{atm}$) than at a control pH_{NBS} of ~ 8.1 ($p\text{CO}_2 \sim 460\text{-}640 \mu\text{atm}$). Moreover, a decrease of $12.0 \pm 5.4\%$ of shell thickness was observed after 15d of development. More severe impacts were found with a decrease of $\sim 0.5 \text{ pH}_{\text{NBS}}$ unit during the first 2 days of development which could be attributed to a decrease of calcification due to a slight undersaturation of seawater with respect to aragonite. Indeed, important effects on both hatching and D-veliger shell growth were found. Hatching rates were $24 \pm 4\%$ lower while D-veliger shells were $12.7 \pm 0.9\%$ smaller at $\text{pH}_{\text{NBS}} \sim 7.6$ ($p\text{CO}_2 \sim 1900 \mu\text{atm}$) than at a control pH_{NBS} of ~ 8.1 ($p\text{CO}_2 \sim 540 \mu\text{atm}$). Although these results show that blue mussel larvae are still able to develop a shell in seawater undersaturated with respect to aragonite, the observed decreases of hatching rates and shell growth could lead to a significant decrease of the settlement success. As the environmental conditions considered in this study do not necessarily reflect the natural conditions experienced by this species at the time of spawning, future studies will need to consider the whole larval cycle (from fertilization to settlement) under environmentally relevant conditions in order to investigate the potential ecological and economical losses of a decrease of this species fitness in the field.

Ries, J.B., Cohen, A.L., and McCorkle, D.C. **A nonlinear calcification response to CO_2 -induced ocean acidification by the coral *Oculina arbuscula*.** *Coral Reefs* 29(3): 661-674, 2010.

Notes: Anthropogenic elevation of atmospheric $p\text{CO}_2$ is predicted to cause the pH of surface seawater to decline by 0.3-0.4 units by 2100 AD, causing a 50% reduction in seawater $[\text{CO}_3^{2-}]$ and undersaturation with respect to aragonite in high-latitude surface waters. We investigated the impact of CO_2 -induced ocean acidification on the temperate scleractinian coral *Oculina arbuscula* by rearing colonies for 60 days in experimental seawaters bubbled with air- CO_2 gas mixtures of 409, 606, 903, and 2,856 ppm $p\text{CO}_2$, yielding average aragonite saturation states (W_A) of 2.6, 2.3, 1.6, and 0.8. Measurement of calcification (via buoyant weighing) and linear extension (relative to a $^{137}\text{Ba}/^{138}\text{Ba}$ spike) revealed that skeletal accretion was only minimally impaired by reductions in W_A from 2.6 to 1.6, although major reductions were observed at 0.8 (undersaturation). Notably, the corals continued accreting new skeletal material even in undersaturated conditions, although at reduced rates. Correlation

between rates of linear extension and calcification suggests that reduced calcification under $W_A = 0.8$ resulted from reduced aragonite accretion, rather than from localized dissolution. Accretion of pure aragonite under each W_A discounts the possibility that these corals will begin producing calcite, a less soluble form of CaCO_3 , as the oceans acidify. The corals' nonlinear response to reduced W_A and their ability to accrete new skeletal material in undersaturated conditions suggest that they strongly control the biomineralization process. However, our data suggest that a threshold seawater $[\text{CO}_3^{2-}]$ exists, below which calcification within this species (and possibly others) becomes impaired. Indeed, the strong negative response of *O. arbuscula* to $W_A = 0.8$ indicates that their response to future $p\text{CO}_2$ -induced ocean acidification could be both abrupt and severe once the critical W_A is reached.

Manzello, D.P. **Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific.** *Coral Reefs* 29(3): 749-758, 2010.

Notes: The rapid growth of scleractinian corals is responsible for the persistence of coral reefs through time. Coral growth rates have declined over the past 30 years in the western Pacific, Indian, and North Atlantic Oceans. The spatial scale of this decline has led researchers to suggest that a global phenomenon like ocean acidification may be responsible. A multi-species inventory of coral growth from Pacific Panama confirms that declines have occurred in some, but not all species. Linear extension declined significantly in the most important reef builder of the eastern tropical Pacific, *Pocillopora damicornis*, by nearly one-third from 1974 to 2006. The rate of decline in skeletal extension for *P. damicornis* from Pacific Panama (0.9% year⁻¹) was nearly identical to massive *Porites* in the Indo-Pacific over the past 20-30 years (0.89 - 1.23% year⁻¹). The branching pocilloporid corals have shown an increased tolerance to recurrent thermal stress events in Panama, but appear to be susceptible to acidification. In contrast, the massive pavonid corals have shown less tolerance to thermal stress, but may be less sensitive to acidification. These differing sensitivities will be a fundamental determinant of eastern tropical Pacific coral reef community structure with accelerating climate change that has implications for the future of reef communities worldwide.

Jury, C.P., Whitehead, R.F., and Szmant, A.M. **Effects of variations in carbonate chemistry on the calcification rates of *Madracis auretenra* (= *Madracis mirabilis sensu* Wells, 1973): bicarbonate concentrations best predict calcification rates.** *Global Change Biology* 16(5): 1632-1644, 2010.

Notes: Physiological data and models of coral calcification indicate that corals utilize a combination of seawater bicarbonate and (mainly) respiratory CO_2 for calcification, not seawater carbonate. However, a number of investigators are attributing observed negative effects of experimental seawater acidification by CO_2 or hydrochloric acid additions to a reduction in seawater carbonate ion concentration and thus aragonite saturation state. Thus, there is a discrepancy between the physiological and geochemical views of coral biomineralization. Furthermore, not all calcifying organisms respond negatively to decreased pH or saturation state. Together, these discrepancies suggest that other physiological mechanisms, such as a direct effect of reduced pH on calcium or bicarbonate ion transport and/or variable ability to regulate internal pH, are responsible for the variability in reported experimental effects of acidification on calcification. To distinguish the effects of pH, carbonate concentration and bicarbonate concentration on coral calcification, incubations were performed with the coral *Madracis auretenra* (= *Madracis mirabilis sensu* Wells, 1973) in modified seawater chemistries. Carbonate parameters were manipulated to isolate the effects of each parameter more effectively than in previous studies, with a total of six different chemistries. Among treatment differences were highly significant. The corals responded strongly to variation in bicarbonate concentration, but not consistently to carbonate concentration, aragonite saturation state or pH. Corals calcified at normal or elevated rates under low pH (7.6-7.8) when the seawater bicarbonate concentrations were above $1800 \mu\text{m}$. Conversely, corals incubated at normal pH had low calcification rates if the bicarbonate concentration was lowered. These results demonstrate that coral responses to ocean acidification are more diverse than currently thought, and question the reliability of using carbonate concentration or aragonite saturation state as the sole predictor of the effects of ocean acidification on coral calcification.

Gao, K.S. and Zheng, Y.Q. **Combined effects of ocean acidification and solar UV radiation on photosynthesis, growth, pigmentation and calcification of the coralline alga *Corallina sessilis* (Rhodophyta).** *Global Change Biology* 16(8): 2388-2398, 2010.

Notes: Previous studies have shown that increasing atmospheric CO₂ concentrations affect calcification in some planktonic and macroalgal calcifiers due to the changed carbonate chemistry of seawater. However, little is known regarding how calcifying algae respond to solar UV radiation (UVR, UVA+UVB, 280-400 nm). UVR may act synergistically, antagonistically or independently with ocean acidification (high CO₂/low pH of seawater) to affect their calcification processes. We cultured the articulated coralline alga *Corallina sessilis* Yendo at 380 ppmv (low) and 1000 ppmv (high) CO₂ levels while exposing the alga to solar radiation treatments with or without UVR. The presence of UVR inhibited the growth, photosynthetic O₂ evolution and calcification rates by 13%, 6% and 3% in the low and by 47%, 20% and 8% in the high CO₂ concentrations, respectively, reflecting a synergistic effect of CO₂ enrichment with UVR. UVR induced significant decline of pH in the CO₂-enriched cultures. The contents of key photosynthetic pigments, chlorophyll *a* and phycobiliproteins decreased, while UV-absorptivity increased under the high pCO₂/low pH condition. Nevertheless, UV-induced inhibition of photosynthesis increased when the ratio of particulate inorganic carbon/particulate organic carbon decreased under the influence of CO₂-acidified seawater, suggesting that the calcified layer played a UV-protective role. Both UVA and UVB negatively impacted photosynthesis and calcification, but the inhibition caused by UVB was about 2.5-2.6 times that caused by UVA. The results imply that coralline algae suffer from more damage caused by UVB as they calcify less and less with progressing ocean acidification.

Udovydchenkov, I.A., Duda, T.F., Doney, S.C., and Lima, I.D. **Modeling deep ocean shipping noise in varying acidity conditions.** *Journal of the Acoustical Society of America* 128(3): EL130-EL136, 2010. **O/A**

Notes: Possible future changes of ambient shipping noise at 0.1-1 kHz in the North Pacific caused by changing seawater chemistry conditions are analyzed with a simplified propagation model. Probable decreases of pH would cause meaningful reduction of the sound absorption coefficient in near-surface ocean water for these frequencies. The results show that a few decibels of increase may occur in 100 years in some very quiet areas very far from noise sources, with small effects closer to noise sources. The use of ray physics allows sound energy attenuated via volume absorption and by the seafloor to be compared.

Reeder, D.B. and Chiu, C.-S. **Ocean acidification and its impact on ocean noise: Phenomenology and analysis.** *Journal of the Acoustical Society of America* 128(3): EL137-EL143, 2010. **O/A**

Notes: Ocean acidification has been observed since the beginning of the industrial era and is expected to further reduce ocean pH in the future. A significant increase in ocean noise has been suggested based upon the percentage change in acoustic absorption coefficient at low frequencies. Presented here is an analysis using transmission loss models of all relevant loss mechanisms for three environments experiencing a significant near-surface pH reduction of 8.1-7.4. Results show no observable change in the shallow water and surface duct environments, and a statistically insignificant change of less than 0.5 dB for all frequencies in the deep water environment.

Joseph, J.E. and Chiu, C.-S. **A computational assessment of the sensitivity of ambient noise level to ocean acidification.** *Journal of the Acoustical Society of America* 128(3): EL144-EL149, 2010. **O/A**

Notes: Low-frequency sound propagating through the ocean is partly attenuated by the pH-dependent boric acid relaxation process. Thus, the uptake of increased levels of atmospheric CO₂ by seawater, leading to reduced pH, has potential to change ambient noise levels. An important question is: By how much? Here, changes in ambient noise level due to hypothetical changes in seawater pH have been calculated at three receiver locations for years 1960 and 2250. The calculations used a range dependent propagation model that was applied to realistic environments based on climatology. Model results indicate changes in noise levels less than 0.21 dB are anticipated.