EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON MARINE ECHINODERMS
**Effects of Ocean Acidification and Warming on Marine Echinoderms**

**Citation:** Center for the Study of Carbon Dioxide and Global Change. "Effects of Ocean Acidification and Warming on Marine Echinoderms.” Last modified March 19, 2014. [http://www.co2science.org/subject/o/summaries/acidwarmechinoderms.php](http://www.co2science.org/subject/o/summaries/acidwarmechinoderms.php).

Most of the ocean acidification research conducted to date has focused solely on the biological impacts of declining seawater pH. Few studies have investigated the interactive effects of ocean acidification and temperature. This summary examines what has been learned in such studies of echinoderms, highlighting several studies that challenge the alarming and negative projections of the IPCC on the matter.

**Gooding et al. (2009)** measured growth rates and feeding rates of juvenile sea stars (*Pisaster ochraceus*) maintained in 246-liter aquaria that were filled with recirculating natural sea water maintained at temperatures ranging from 5 to 21°C, and which were constantly bubbled with either ambient air of 380 ppm CO\(_2\) or CO\(_2\)-enriched air of 780 ppm CO\(_2\). Results indicated that "the relative growth (change in wet mass/initial wet mass) of juvenile *P. ochraceus* increased linearly with temperature from 5°C to 21°C," and that it also responded positively to atmospheric CO\(_2\) enrichment. More specifically, the authors state that "relative to control treatments, high CO\(_2\) alone increased relative growth by ~67% over 10 weeks, while a 3°C increase in temperature alone increased relative growth by 110%." They also state that increased CO\(_2\) "had a positive but non-significant effect on sea star feeding rates, suggesting CO\(_2\) may be acting directly at the physiological level to increase growth rates." Last of all, their data show that the percentage of calcified mass in the sea stars dropped from approximately 12% to 11% in response to atmospheric CO\(_2\) enrichment at 12°C, but that it did not decline further in response to a subsequent 3°C warming at either ambient or elevated CO\(_2\). In light of such observations the three Canadian researchers say their findings demonstrate that "increased CO\(_2\) will not have direct negative effects on all marine invertebrates, suggesting that predictions of biotic responses to climate should consider how different types of organisms will respond to changing climatic variables." Indeed, they clearly state -- and without equivocation -- that

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"responses to anthropogenic climate change, including ocean acidification, will not always be negative."

Wood et al. (2010)² studied a number of physiological parameters in the serpent starfish (Ophiura ophiura). In doing so, they collected 96 individuals with a disc diameter between 10 and 15 mm from Cawsand Bay, Plymouth Sound (50°C09.77' N, 4°C11.50' W), after which they exposed the brittlestars to three different pH treatments (pH of 8.0, 7.7 or 7.3) and two different temperature treatments (10.5°C or 15°C) for a period of 40 days. Measured parameters included metabolism, calcification, mortality, motility, arm structure, and arm regeneration, the latter of which parameters was studied by removing either 10, 20, 30, or 40 mm of arm length on one of the animals' arms.

Results of the experiment revealed the following: (1) survival was "100% at both temperatures and across all pH treatments," (2) metabolic rate increased as pH decreased in the low temperature treatment, while there was no significant difference across the different pH treatments in the high temperature regime, (3) muscle appearance and density did not change over either the temperature or pH treatment ranges in established or regenerated arms, (4) a faster response time in movement (motility) was observed at low temperature and low pH, (5) brittlestars across "all treatments had the same net calcification throughout the experiment," (6) arm regeneration rate within the low temperature treatment was "unaffected by the length of arm lost and the rate was similar between all pH treatments," (7) arm regeneration rate was significantly faster at higher temperatures than lower temperatures. In light of such findings, it would appear that the serpent starfish should be able to successfully cope with the physiological changes brought about by any modest temperature increase and/or pH decline likely to occur in the future.

Working with adult specimens of the intertidal seastar Parvulastra exigua that were collected from Little Bay, Sydney (Australia), McElroy et al. (2012)³ measured the metabolic rates of the seastars at conditions characteristic of high tide (ca. 18°C and pH 8.2), as well as at 3 and 6°C warmer conditions and at additional pH values of 7.8 and 7.6 "in all combinations." The

measurements revealed that "the metabolic response of *P. exigua* to increased temperature (+3°C and +6°C) at control pH [8.2] indicates that this species is resilient to periods of warming as probably often currently experienced by this species in the field." And they also report that they "did not observe a negative effect of acidification on rate of oxygen consumption at control temperature, a combination of stressors that this species currently experiences at night time low tide."

Although the metabolic response of *P. exigua* is resilient to current levels of *extreme* temperature and pH stress - which are equivalent to *mean* conditions predicted for the end of the 21st century - it is possible that the *extreme* seawater temperatures and pH levels at that future time (if IPCC predictions prove true) will be *greater* than the extreme levels of today, which could prove to be a real challenge for the seastars. However, McElroy *et al.* write, in the concluding paragraph of their research report, that "species such as *P. exigua* with a broad distribution from warm to cold temperate latitudes may possess scope for adaptation (evolutionary change) and/or acclimation via phenotypic plasticity (Visser, 2008), as suggested for sympatric echinoid and ophiuroid species (Byrne *et al.*, 2011; Christensen *et al.*, 2011)."

Brennand *et al.* (2010)\(^4\) reared embryos of the sea urchin *Tripneustes gratilla* in flow-through chambers filled with filtered seawater maintained at all combinations of three different temperatures (24, 27 and 30°C) and three different pH values (8.15, 7.8 and 7.6), where the 24°C/pH 8.15 combination represented normal control conditions. Then, after five days of such exposure, the growth and development of the larvae were assessed.

Results of the experiment revealed that "larvae reared at pH 7.6 and pH 7.8 had smaller post oral arms when compared with those reared at control pH." However, they report that "a +3°C warming diminished the negative effects of low pH/high CO\(_2\)," as was "seen in the similar post oral arm length of larvae treated at 27°C/pH 7.6 and 27°C/pH 7.8 and those reared in control temperature and pH." In addition, they say that "as total length of calcite rods is largely comprised of the post oral arms, this measure [of calcification] followed a similar pattern."

The results of this study suggest that the negative effects of a 0.35 to 0.55 CO\(_2\)-induced decline in seawater pH on the growth and calcification of the sea urchin *Tripneustes gratilla* can be largely overcome by a 3°C increase in water temperature. And since an analysis of Tans (2009) suggests that the maximum decline in seawater pH that will likely ever be produced by the burning of fossil fuels will be somewhere in the range of only 0.1 to 0.18 in the vicinity of AD 2100 (after which pH begins to slowly rebound), there would seem to be little reason for concern about any negative impact of rising atmospheric CO\(_2\) concentrations on this particular species of sea urchin, which is widely distributed throughout the Indo-Pacific region and is well suited for production by aquaculture (Lawrence and Agatsuma, 2007; Juinio-Menez *et al.*, 1998; Dworjanyn *et al.* 2007).

Byrne *et al.* (2009)\(^5\) investigated the effects of ocean acidification state (pH values of 8.2–7.6, corresponding to atmospheric CO\(_2\) concentrations of 230-690 ppm) and seawater temperature

\(^4\) http://www.co2science.org/articles/V13/N34/B2.php.

(20-26°C, where 20°C represents the recent thermal history of indigenous adults) on the fertilization of sea urchin (*Heliocidaris erythrogramma*) eggs and their subsequent development in what they call "the eastern Australia climate change hot spot," which is located near Sydney.

According to the authors, over the ranges of seawater pH and temperature they studied, there was "no effect of pH" and "no interaction between temperature and pH" on sea urchin egg fertilization. Seawater pH also had no effect on the longer-term development of fertilized sea urchin eggs; but the six scientists say that warming led to "developmental failure at the upper warming (+4 to +6°C) level, regardless of pH." Even here, however, they appear quite hopeful, stating that "it is not known whether gametes from *H. erythrogramma* adults acclimated to 24°C would have successful development in a +4°C treatment," stating that their study "highlights the potentiality that adaptive phenotypic plasticity may help buffer the negative effects of warming, as suggested for corals." In fact, they note that "single stressor studies of thermotolerance in a diverse suite of tropical and temperate sea urchins show that fertilization and early development are robust to temperature well above ambient and the increases expected from climate change," citing the work of Farmanfarmaian and Giese (1963), Chen and Chen (1992) and Roller and Stickle (1993).

Also exploring the topic of reproduction, Byrne *et al.* (2010a) examined the interactive effects of near-future (ca. AD 2070-2100) ocean warming (temperature increases of 2-6°C) and ocean acidification (pH reductions of 0.2-0.6) on fertilization in four intertidal and shallow subtidal echinoids (*Heliocidaris erythrogramma*, *Heliocidaris Tuberculata*, *Tripneustes gratilla*, *Centrostephanus rodgersii*), an asteroid (*Patiriella regularis*) and an abalone (*Haliotis coccoradiata*), working with batches of eggs they collected from multiple females that were fertilized by sperm obtained from multiple males, all of which entities were maintained and employed in all combinations of three temperature and three pH treatments. Results indicated, in the words of the eight researchers, that "there was no significant effect of warming and acidification on the percentage of fertilization." In light of their findings, Byrne *et al.* say their results indicate that "fertilization in these species is robust to temperature and pH/PCO2 fluctuation," while opining that their findings "may reflect adaptation to the marked fluctuation in temperature and pH that characterizes their shallow water coastal habitats."

In another fertilization study, Byrne *et al.* (2010b) investigated the effects of projected near-future oceanic warming and acidification of the sea urchin *Heliocidaris erythrogramma* for conditions that have been predicted for southeast Australia within the timeframe of 2070-2100: an increase in sea surface temperature of 2 to 4°C and a decline in pH of 0.2 to 0.4 unit. This was accomplished via multi-factorial experiments that incorporated a titration of sperm density ($10^3$ sperm per ml) across a range of sperm-to-egg ratios (10:1-1500:1). Results indicated that "across all treatments there was a highly significant effect of sperm density, but no significant effect of temperature or interaction between factors." In fact, they state that "low pH did not reduce the percentage of fertilization even at the lowest sperm densities used, and increased temperature did not enhance fertilization at any sperm density." In addition, they remark that "a number of ecotoxicology and climate change studies, where pH was..."
manipulated with CO₂ gas, show that sea urchin fertilization is robust to a broad pH range with impairment only at extreme levels well below projections for ocean acidification by 2100 (pH 7.1-7.4, 2,000-10,000 ppm CO₂)," citing the work of Bay et al. (1993), Carr et al. (2006), and Kurihara and Shirayama (2004). Because neither seawater warming nor seawater acidification (caused by contact with CO₂-enriched air) had either a positive or a negative effect on sea urchin fertilization, the five scientists conclude that "sea urchin fertilization is robust to climate change stressors."

According to Caldwell et al. (2011)⁸, "the reproductive processes and early life-stages of both calcifying and non-calcifying animals are believed to be particularly vulnerable to a reduced pH environment," but they say "there is as yet no clear and reliable predictor for the impacts of ocean acidification on marine animal reproduction." Therefore, as their contribution to the subject, Caldwell et al. "investigated the combined effect of pH (8.06-7.67) and temperature (14-20°C) on percent sperm motility and swimming speed in the sea urchin Psammechinus miliaris using computer assisted sperm analysis (CASA)," while working with specimens they collected from the Isle of Cumbrae (Scotland). "Surprisingly," in the words of the six scientists, "sperm swimming performance benefited greatly from a reduced pH environment," as "both percent motility and swimming speeds were significantly enhanced at pHs below current levels." And in light of the additional fact that sperm-activating peptides - which are believed to have evolved some 70 million years ago during a period of high atmospheric CO₂ concentration - are fully functional from pH 6.6 to 8.0 (Hirohashi and Vacquier, 2002), they state that "the combined data on motility, swimming speed and SAP function at reduced pH indicates that sperm are sufficiently robust to allow functionality at pHs that would have been experienced in the paleo-ocean (ca pH 7.4-7.6) and which are within projections for near-future climate change scenarios." Thus, the UK researchers conclude that "current ocean pH levels are suboptimal for P. miliaris sperm-swimming speed and that reproductive success for certain marine species may benefit from a reduced pH ocean."

Ericson et al. (2012)⁹ examined the interactive effects of warming and acidification on fertilization and embryonic development of the ecologically important sea urchin Sterechinus neumayeri reared from fertilization in elevated temperature (+1.5°C and 3°C) and decreased pH (-0.3 and -0.5 pH units). Results of their analysis indicate that "fertilization using gametes from

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multiple males and females, to represent populations of spawners, was resilient to acidification at ambient temperature (0°C)," and they say that development to the blastula stage was "robust to levels of temperature and pH change predicted over coming decades." The sea urchins studied by the seven scientists thus appear well equipped to successfully deal with IPCC-predicted near-future increases in seawater temperature and acidification; and whatever may happen beyond the current century should prove to be of little problem as well.

In prefacing their work, authors Foo et al. (2012) write that "selection by stressful conditions will only result in adaptation if [1] variation in stress tolerance exists within a population, if [2] tolerance of stressors is heritable, and if [3] changes in tolerance traits are not constrained by negative genetic correlations with other fitness traits," citing references both old and not so old: Darwin (1859) and Blows and Hoffmann (2005).

In harmony with these principles, Foo et al. (2012)\textsuperscript{10} "quantified genetic variation in tolerance of early development of the ecologically important sea urchin Centrostephanus rodgersii to near-future (2100) ocean conditions projected for the southeast Australian global change hot spot," wherein "multiple dam-sire crosses were used to quantify the interactive effects of warming (+2-4°C) and acidification (-0.3-0.5 pH units) across twenty-seven family lines" of the species. In doing so, the four Australian researchers report that "significant genotype by environment interactions for both stressors [warming and acidification] at gastrulation indicated the presence of heritable variation in thermal tolerance and the ability of embryos to respond to changing environments." And they say that "positive genetic correlations for gastrulation indicated that genotypes that did well at lower pH also did well in higher temperatures." Thus, in the concluding paragraph of their paper, Foo et al. affirm that "the presence of tolerant genotypes, and the lack of a trade-off between tolerance to pH and tolerance to warming contribute to the potential of C. rodgersii to adapt to concurrent ocean warming and acidification, adding to the resilience of this ecologically important species in a changing ocean."

The several studies highlighted above suggest that rising sea temperatures and a lowering of the pH of the ocean's surface waters will prove less of a problem to echinoderms than the IPCC projects. In fact, for many echinoderm species, it may well prove to be a non-problem.

\textsuperscript{10} http://www.co2science.org/articles/V16/N7/B1.php.
REFERENCES


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