2010 Sendai Ocean Acidification Workshop

by Kenneth Denman, Yukihiro Nojiri and Hans-Otto Pörtner

The oceans are becoming acidified as carbon dioxide from fossil fuel emissions enters surface ocean waters from the atmosphere. Global surface pH has already decreased by more than 0.1 units, (IPCC WG1 AR4 Report, Chapter 5, 2007), and may decrease by another 0.4 units by the end of this century under the high CO_2 emission scenario. Some regions of the ocean may have a significant decrease in the $CaCO_3$ saturation state even with the same atmospheric CO_2 change. The key question that should be addressed in future studies on the effects of increasing $P\mathrm{CO_2}$ in the ocean may be stated as: What will be the responses and adaptive capacities of individual species and whole ecosystems to a multi-decadal decrease in pH of 0.1–0.5 units?

A 1-day workshop on "*Potential impacts of ocean acidification on marine ecosystems and fisheries*", co-convened by the authors of this article, was held immediately prior (April 25, 2010) to the International Symposium on "*Climate change effects on fish and fisheries*" in Sendai, Japan. Talks and posters presented at the workshop reported on manipulation experiments and observations on the effects of elevated CO_2 on organisms at all trophic levels of fisheries foodwebs, and modelling approaches to predict the impact of continuing increases in atmospheric CO_2.

The first talk (Denman *et al*.) presented observational evidence of open ocean increases in $P\mathrm{CO_2}$ and decreases in pH, followed by model projections of global mean and spatial patterns of the decrease in pH until the end of this century. Several talks and posters reported on studies of organisms with calcium carbonate skeletal structures subjected to various experimental exposures to low pH (high $P\mathrm{CO_2}$) waters in controlled laboratory or field situations. Other talks and posters described physiological and behavioural responses of animals to elevated CO_2 conditions. One poster evaluated the adequacy of a number of ecosystem models to simulate adaptation over long time scales to changes in CO_2 (and other related variables) associated with climate change.

Nakamura *et al*. reported on a depression of metabolism and growth in coral larvae with elevated CO_2 levels. Similiary, Lartey-Antwi and Anderson found decreased growth rates of flat-tree oysters. Suwa and Shirayama presented data obtained with a system precisely mimicking constant and fluctuating CO_2 levels, where the fluctuating levels showed less impact on the growth and skeletal structures of echinoderm larvae than CO_2 levels set permanently high. Kurihara provided an overview on different levels of CO_2 sensitivities according to taxon and in early life stages. Ishimatsu *et al*., Munday *et al*. and Dissanayake *et al*. reported on changes in various processes indicating tolerance limits, decreased aerobic scope and behavioural changes in shrimp and young fish in response to elevated CO_2 levels, with species-specific differences even among closely related fish species. Salau introduced a model of reduced carrying capacity for pteropods as pH decreases, and the feedback effects on pink salmon: as a result, even and odd year differences in salmon stock size will increase over time with management implications for repeating strong and weak returns in alternating years. Rumrill *et al*. (poster) presented long-term observations of an estuary showing decreasing pH and effects on oysters in the outer saline estuary and increasing pH probably resulting from changes in precipitation and freshwater runoff. Takami *et al.* demonstrated how elevated CO_2 levels

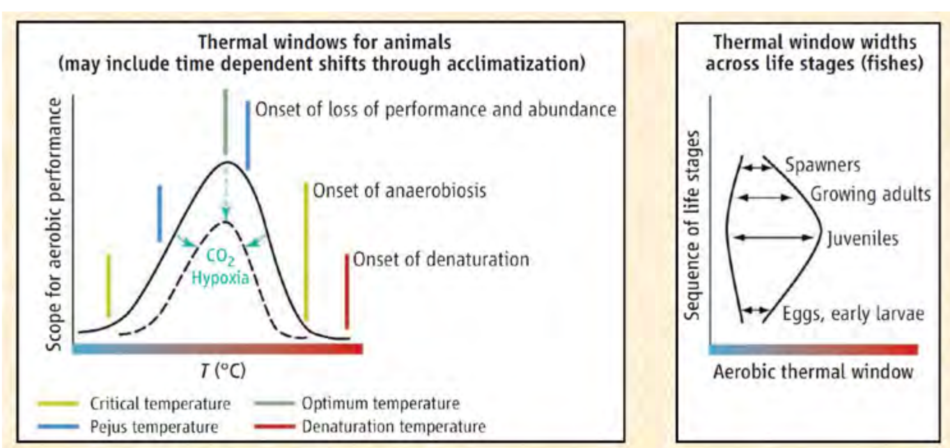

Fig. 1 Animal physiology and climate change showing (left panel) how the 'thermal window' for normal activity by marine animals may shrink with decreasing oxygen concentrations and increasing CO_2 concentrations, and (right panel) how the thermal window changes with life stage (from Pörtner and Farrell, 2008, Science, 322, 690–692) [see page 31].

slow and disturb development in abalone, and Sugie *et al.* (poster) found enhanced drawdown in Si/N by Bering Sea phytoplankton as pH fell and Fe was limited. Kim and Kim (poster) used brine shrimp as a model for identifying changes in the expression of individual genes during exposure to low pH. Finally, Le Quesne and Pinnegar (poster) analyzed several ecosystem models, emphasizing that parameterizations of various physiological processes would be needed to support the evaluation of responses to changing pH.

Noteworthy findings can be summarized as follows:

- Overall, investigators are observing different sensitivity levels among investigated organisms (some closely related), ranging from calcification and growth to development, behaviours and ecosystem level responses. The consideration and introduction of environmental variability changes the pattern and level of response. In light of the complexity and diversity of responses observed, it is thus too early to draw general conclusions regarding the responses of ecosystems to elevated CO_2.
- The inclusion of pre-industrial levels (around 280 ppm CO_2) in experimental protocols, as well as the precise control of diel CO_2 cycling, was considered highly valuable in studying the impact of ocean acidification. In fact, one study reported improvement in calcified structures in echinoderm larvae under pre-industrial compared with present-day levels of ambient CO_2. Investigations of mechanisms under high $P\mathrm{CO_2}$ need be complemented by testing the role of such responses under expectable $P\mathrm{CO_2}$ according to ocean acidification scenarios.
- Studies of behavioural and physiological responses to elevated CO_2 levels for organisms that are not necessarily calcifiers are less mature, but are exciting because so little is known.

Recommendations and Key Questions from the workshop include:

- Pre-industrial control runs should be done more often, since organisms have already adapted from that point.
- Experiments often include current day $P\mathrm{CO_2}$ (~380 ppm) and an elevated CO_2 level of ~1000 ppm. If emissions are controlled to try to achieve <3°C global warming, then intermediate levels of, say, 450, 550, and 700 ppm, have to be considered. Both these recommendations require precise $P\mathrm{CO_2}$ (pH) control.



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- Long period culture experiments/multi-generation studies are both needed to try to obtain information on long term adaptive capacity and evolutionary change, but are usually restricted to species with generation times of less than 1 year. Comparisons of species from various climate regimes and CO_2 environments may help to circumvent these constraints in long-lived species.
- In experimental studies diel, seasonal and inter-annual variability of CO_2 levels should be simulated, if relevant for the respective ecosystem. Such experiments would be required to identify slow trends embedded in highly variable environments.
- Population genetic and functional genomic analyses need to be applied more widely.
- Models have to be examined as to whether they formulate physiological and behavioural processes that are dependent on changing environmental drivers such as P_{CO_2} or temperature.
- Some aquaculture species respond differently than their "wild" counterparts. Have they already become adapted to higher P_{CO_2}, for example by being cultured in water supplied from depths below the mixed layer that already has elevated P_{CO_2} relative to the depths at which the wild populations live?
- Can we learn from species already experiencing higher P_{CO_2} naturally? For example some species of copepods and euphausiids migrate several hundreds of meters vertically on diel and seasonal timescales (diapause), where at depth they are exposed to P_{CO_2} levels of 500 to 1000 ppm.
- Very importantly, experimental protocols must include behavioural and physiological dependencies on multiple variables that we expect to change with the climate: P_{CO_2}, dissolved oxygen, temperature, micro-nutrients (Fe), *etc*. [*e.g.*, see Fig. 1 showing a shrinking "thermal window" (aerobic scope – difference between maximal and resting metabolic rates) with decreasing O_2 and increasing P_{CO_2} (and temperature?)].
- Sensitivities need to be systematically identified across taxa and in between species comparisons.
- Through a combined experimental and modeling approach, can we start to evaluate possible changes in whole ecosystem structure resulting from the possible disappearance and replacement of key species?