Effects of CO$_2$ on marine animals

Time scales, processes, and limits of adaptation

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Scenarios:
- Business as usual,
- Direct disposal,
- Indirect disposal (Fe fertilization)

Interactions with temperature and hypoxia regimes
Principle considerations:
Role of time scales in CO₂ exposure experiments

†Asphyxiation: squid and fish

Mortality dependent on CO₂ level and exposure time

Incipient lethal CO₂ level (LD₅₀)
(long term critical threshold)

Zone of resistance

Mortality independent of exposure

Upper median lethal CO₂ level (LD₅₀)

log exposure time (days, weeks, months, years) →

No such complete data set exists

critical level and mechanism unknown

Tolerable organism and ecosystem (?) responses

Pörtner, in prep.
Example of an animal species tolerant to CO$_2$ oscillations: *Sipunculus nudus*

eurybathic: found between 0 and 2300 m depths
However, tolerance is limited: Delayed onset of enhanced mortality during long term „disturbed“ maintenance under 1 % CO₂ in *S. nudus*

- no decrease in body energy stores
- behavioral incapacitation involved

Langenbuch et al. (2004)
Permian-Triassic mass extinctions

Loss of marine invertebrate genera due to CO₂?

Physiological characters of eliminated forms?

moderately active, moderate calcification

(sessile, hypometabolic, calcified: larger effect?)

CO₂ limitations relevant in evolution?

after Knoll et al., 1996
**Physiological background??**

*S. nudus*: Extra- and intracellular acid-base status during hypercapnia *in vivo*

Partial compensation of extracellular acidosis: A typical finding in invertebrates?

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**Graph:**
- **pH_{pl}** and **pH_{i}** values plotted against time (h) ranging from 0 to 144.
- **1 % CO_{2}** is indicated as a 1 % increase in CO_{2} levels.
- **Partial compensation** and **full compensation** stages are highlighted.
- **Control** values are shown for comparison.

After Pörtner et al. 1998.
55 % (!) growth reduction in *Mytilus galloprovincialis* under hypercapnia (permanent extracellular acidosis!!)

Water pH 7.3: Maximum pH drop as expected from business as usual scenarios by 2300 (Caldeira and Wickett, 2003)

Michailidis et al. (2004)
Close correlation between dry / wet weight and shell length

Reduced growth affects shell and soft body alike

Michailidis et al. (2004)
Reduced cellular protein synthesis during acidosis favouring amino acid catabolism in *S. nudus* ....likely causing reduced growth rates

Mytilus galloprovincialis under hypercapnia (water pH 7.3):

65% (!) metabolic depression associated with enhanced N excretion, i.e. protein degradation during permanent (extracellular) acidosis (as seen in S. nudus)

Michailidis et al. (2004)
Uncompensated intracellular acidosis in cuttlefish (*S. officinalis*) brain under 24 h of hypercapnia (1%)

Animals died despite return to normocapnia!!!
Uncompensated acidosis and metabolic depression in several invertebrates ...
contributing to lower resistance and enhanced mortality?

Compensated acidosis and, therefore, no metabolic depression in most fish ...
a reason for enhanced resistance to high CO$_2$?

Heisler, 1986, Larsen et al. 1997, Ishimatsu et al., 2004
Mortality involves metabolic and behavioral depression caused by adenosine accumulation in nervous tissue of *S. nudus*.

A role for adenosine in metabolic depression.

<table>
<thead>
<tr>
<th>Infusion</th>
<th>Adenosine (nmol·g nervous tissue⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1nmol·g⁻¹·h⁻¹</td>
</tr>
<tr>
<td>Anoxia</td>
<td>5nmol·g⁻¹·h⁻¹</td>
</tr>
<tr>
<td>Hypercapnia</td>
<td>8nmol·g⁻¹·h⁻¹</td>
</tr>
<tr>
<td>Anoxia + Hypercapnia</td>
<td>10nmol·g⁻¹·h⁻¹</td>
</tr>
</tbody>
</table>

Reipschläger et al., 1997

Reduced exercise capacity and activity.
Unifying principles of CO₂ effects in animals

still incomplete!!

Pörtner et al. 2004
A recent hypothesis:
The first level of thermal intolerance at low and high temperature extremes in METAZOA is a loss in whole organism aerobic scope, a unifying principle in ectotherms (!) and endotherms (!?).

Naturw. 88, 137-146, 2001
Am. J. Physiol. 283, R1254- R1262, 2002
Comp. Biochem. Physiol. 132A, 739-761, 2002
**O₂ dependent temperature limits verified across phyla:**
annelids, sipunculids, molluscs (bivalves, cephalopods), crustaceans, fish and some air breathers, limited evidence in endotherms incl. man.

**EXAMPLES**

- **Temperate crustacean,** *Maja squinado*
- **Temperate cephalopod,** *Sepia officinalis*
- **Antarctic bivalve,** *Laternula elliptica*
- **Atlantic cod,** *Gadus morhua*
- **Antarctic and temperate zoarcids,** *Pachycara brachycephalum, Zoarces viviparus*

Cephalopod mantle tissue, a large ventilatory muscle
Ventilatory muscle capacity limiting at critical temperatures

Hypoxia, CO₂, and thermal extremes act synergistically via the same physiological mechanisms!!

Aerobic scope and performance are maximal at the upper peius temperature.

Hypoxia, CO₂, and thermal extremes act synergistically affecting growth, exercise, behaviours, reproduction, behaviours, ...fitness
Processes and Limits: Effects of integrated CO$_2$, O$_2$ and temperature fluctuations

CO$_2$ impacts on:

Hypoxia tolerance ↑
→ Improved extension of passive survival (limited!)

BUT

Aerobic scope ↓
→ Long term performance and growth functions ↓
→ Thermal tolerance ↓
(tolerance to thermal fluctuations ↓)

These interactions and not CO$_2$ alone have likely shaped evolutionary scenarios!

Pörtner and Langenbuch, in prep.
Animal limitations in high CO₂ oceans

Progressive (not beyond critical thresholds?) effects already expected in 450 to 750 ppm surface ecosystems shifted ecosystem equilibria caused by:

- reduced calcification rates
  - higher ratios of non-calcifiers over calcifiers
- reduced tolerance to thermal extremes
  - enhanced geographical distribution shifts
  - reduced distribution ranges
- reduced behavioral capacity, growth, productivity and life span*
  - food chain length and composition*
  - reduced population densities, ……biodiversity (critical!)??

*effects transferred to deep with ocean disposal (direct and indirect)
Research needs to further identify mechanisms, titrate/quantify (lab and field) scenarios, address micro-evolutionary potential

Pörtner and Langenbuch, in prep.
Ocean CO₂ disposal: Are their methods of choice?

Preliminary insight from CO₂, T, hypoxia impact studies in animals

- Avoid business as usual scenarios
  - (thermal changes, direct impact of CO₂!)
- Avoid large scale disposal strategies
  - (towed pipe or Fe fertilization)
- If feasible, use CO₂ lake option in environments protected from physical disturbance („dump site“ strategy)
- Apply direct pH neutralization of injected CO₂?
- Dispose in thermally stable environments
- Avoid hypoxia aggravation (eutrophication)

Pörtner and Langenbuch, in prep.
CLIMATE CHANGE, CO₂ effects, ENERGY BUDGETS

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