Effect of high CO$_2$ on the metabolism of jumbo squid *Dosidicus gigas*

Rui Rosa, Brad Seibel

Department of Biological Sciences, University of Rhode Island
Bio-ecological background

- *Dosidicus gigas* is a powerful squid that reaches 2-3 m TL and 50 kg.
- Seasonal and diurnal migrations;
  - **Daytime** in deep, cold and oxygen-depleted water (OML; ~10 °C at 300 m)
  - **Night** in shallow, warm (up to 30 °C) and aerated waters.
Bio-ecological background

- Spawning areas have not been definitely identified.

- Egg masses were observed in nature for the first time in June 2006 (Sea of Cortez).
Mass-specific metabolic rates ($B$) typically decline with increasing body mass ($M$) according to:

$$B = b_0 M^b,$$

$b_0 = \text{normalization constant (independent of mass)}$

$b = \text{scaling coefficient (-0.25 is widely accepted as a biological law)}$
Metabolic scaling

- Specimens ranged from 0.03 to 12000 g (7 orders of magnitude)

- Syringes (<0.05g)
- Flow-through chambers (2 to 50g)
- Swimming tunnel (> 2000g)
**Routine metabolic scaling**

\[ B = 12.75x^{-0.0615} \ (n=34) \]

...B rates unmatched by most aquatic ectotherms and mammals (at comparable °C). High oxygen demand is due to the less efficient mode of swimming (jet propulsion).
**Metabolic scaling**

### D. gigas

\[ y = 12.75x^{0.0615} \]

<table>
<thead>
<tr>
<th>Other Groups</th>
<th>b</th>
<th>( b_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loliginidae</td>
<td>-0.084</td>
<td>8.2</td>
</tr>
<tr>
<td>Ommastrephidae</td>
<td>-0.078</td>
<td>7.6</td>
</tr>
<tr>
<td>Gonatidae</td>
<td>-0.02</td>
<td>4.6</td>
</tr>
<tr>
<td>Cranchidae</td>
<td>-0.19</td>
<td>0.53</td>
</tr>
<tr>
<td>Octopodidae</td>
<td>-0.27</td>
<td>3.3</td>
</tr>
<tr>
<td>Bolitaenidae</td>
<td>-0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>Vampyroteuthidea</td>
<td>-0.23</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*Source: Seibel J. Exp. Biol. (in press)*

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Closer to isometry
Metabolic scaling

Explanation 1 - Tubular geometry and exchange surfaces.

While important to other cephalopods species, body mass is less relevant to squid’s mass-specific metabolism (namely of neritic and epipelagic ones).

Mantle diameter increases faster than thickness with growth.

Surf. Area^{1/2} : Volume^{1/3} increases with size (O’Dor and Hoar, 2001)

Exchange surfaces are well suited (mitochondrial distribution) for cutaneous oxygen uptake (~60%, Pörtner 2002).
Metabolic scaling

The near-isometric scaling of S.A. to Vol. ratios and reliance on cutaneous respiration may be the critical determinants of squid’s metabolic scaling.
Metabolic scaling

Explanation 2 – Ontogenetic differences on locomotory expenditure.

Squid’s cost of transport may not decrease as much with size as in other animals (e.g. mammals, birds and fish) where adults are more energy-efficient.

. The open ocean biota may be favouring the evolution of isometric scaling in pelagic invertebrates (Glazier 2006).

. Large inter-specific differences in $B_0$ (from 0.1 to $12.7$ - *D. gigas*) seem to imply distinct locomotory demands – a consequence of species’ life-style and ecology.
Metabolic scaling

Explanation 3 – Energetic requirements during all stages of the squid’s short-life cycle (namely to growth and reproduce)

High sustained production costs during at all ages may result in a \( B \) value that does not decrease with increasing body mass.

Is it adequate to generalize \textit{quarter-power law} (in “Metabolic Theory of Ecology”)?
Part 2. Effect of high CO$_2$ on the metabolism of D. gigas

\[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \]
\[ \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \]
\[ \text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-} \]
CO$_2$ and ocean pH

- Prior to industrial revolution: atm [CO$_2$] 280 ppm
- Current atmospheric [CO$_2$] $\sim$ 360 ppm
- Expected to rise 1% y$^{-1}$ over the next few decades (Houghton et al., 2001)
- Simulated atm CO$_2$ exceeds 1900 ppm at around the year 2300 (Caldeira and Wickett, 2003)
CO₂ and ocean pH

. 50% of human emissions remain in the atmosphere

Other 50%:

30% dissolved in the oceans + 20% terrestrial biosphere

. When CO₂ dissolves in the ocean lowers the pH (more acidic)

. Over the coming centuries oceans will experience pH changes greater than in the last 300 Myr.
Impact of CO$_2$ on the marine biota

. Coral reefs and other marine calcifiers (i.e. with CaCO$_3$ structures) are particularly affected (↓ [CO$_3^{2-}$] with ↑ [CO$_2$])

. CO$_2$ enters the organism by diffusion. If compensation of acid-base imbalance is not achieved (transport of acid-base equivalent ions across cell membranes)

↓ Metabolic Depression

. ↑CO$_2$ lowered blood oxygen binding capacity of Illex illecebrosus (Pörtner and Reipschläger, 1996)
Effect of high CO$_2$ on metabolism of D. gigas

. Flow-through respirometry - squids ranging from 2 to 50g

. Seawater was acidified by bubbling an air mix with 0.1% CO$_2$ (conc. expected to be attained in 100 years)
Effect of high CO\textsubscript{2} on D. gigas

Consequence of time spent in the chamber?

A new cycle was added

Specimen 1 (13.4g)

Specimen 2 (50.8g)
Effect of high CO$_2$ on D. gigas
Effect of high CO$_2$ on $D$. gigas

**Standard Metabolic rate – SMR**

<table>
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<tr>
<th>Mass (g)</th>
<th>MO2 (μmol h$^{-1}$ g$^{-1}$)</th>
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<td>Normal</td>
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**Routine Metabolic rate – RMR**

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**“Active” Metabolic rate – AMR**

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<th>Mass (g)</th>
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</tr>
</thead>
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<tr>
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<td>Hig h CO$_2$</td>
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(n=7; p>0.05)
Effect of high CO$_2$ on D. gigas

% Decrease (from Normal to High CO$_2$ - 2nd cycle)

- SMR: 3.4
- RMR: 8.9
- AMR: 10.3
Effect of high $\text{CO}_2$ on $D. \text{gigas}$
Effect of high CO$_2$ on $D. \ gigas$

![Graph showing the effect of high CO$_2$ on $D. \ gigas$. The graph includes boxes representing normal and high CO$_2$ conditions, with percentage changes indicated.](image-url)
Discussion

. The lowering of squid’s metabolism (namely RMR and AMR) seemed evident, also with the reduction of Nc h\(^{-1}\) and scope for activity.

Great sensitivity to small changes in CO\(_2\)

. Squid’s respiratory protein (hemocyanin) seems to need fine tuning of pH to allow efficient oxygen transport (large Bohr effect).

. On-going experiments should demonstrate lowered blood oxygen binding capacity caused by elevated CO\(_2\).
Discussion

- Quantification of octopine production may show the eventual switch to anaerobic energy production.

Ineffective under chronic elevation of anthropogenic CO$_2$

- The short-term *sublethal effect* (metabolic depression) may have serious impact on predatory behavior.

Lower swimming activity will imply lower predator-prey (primarily myctophid fish) interactions.
Long-term effects will include reduced growth rates and reproductive output

Cascading impacts to the top of the food-web will be expected (prey for many vertebrates, ranging from sharks and bony fishes to marine mammals).
Discussion

Direct effects on fish?

In comparison to squid, fish are better protected from CO$_2$ effects:

. **Lower metabolic rates** (associated with undulatory swimming);

. **Hemoglobin** is located in erythrocytes, where is more protected from extracellular pH disturbances by the great capacity of intracellular acid-base regulation.
Conclusions

Elevated environmental CO$_2$ and the consequent acidification seemed to interfere with this squid’s respiratory physiology, which may have cascading and long-term impacts on its biology and ecology.
Acknowledgments

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Thank You!!