The Ocean in a High CO$_2$ World Symposium
Monaco, 6-9 October 2008

Science Summary of the Symposium for Policy Makers

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What is Oceanic Acidification?

The Oceans are becoming more acid as they take up more CO₂

The Ocean Acidification Timeline ……
While climate change has uncertainty, these geochemical changes are highly predictable.

Oceans are an important reservoir for CO₂ with c. 30% of CO₂ produced from fossil fuel burning & land-use change taken up by oceans (Sabine et al. 2004 Science) – effectively buffering climate change.

CO₂ produced by humans is predicted to decrease surface ocean pH by 0.4 +/- 0.1 depending on scenario by 2100.

pH has already changed by 0.1 in surface waters due to absorption of anthropogenic CO₂ - equivalent to 30% increase in acidity.

……the Oceans are Acidifying Fast

It is happening now, at a rate and to a level not experienced by marine organisms for ~20MY perhaps even 100’s MY

Turley et al. (2006) Avoiding Dangerous Climate Change
Learning From the Past – Are There Clues to Future Impacts?

- Mass extinctions linked to previous ocean acidification events
- Takes millions of years to recover

"Today is a rare event in the history of the World"
Ocean Acidification is Happening Now and is Measurable ……

- CO₂ in oceans increases with increasing atmospheric CO₂: this is certain!

Observed trends indicate possible impacts already emerging in:

- Shell weight decrease with time in Pteropods, Foraminifera and Brachiopods
- Reduced calcification in coral reefs from GBR over last 2 decades
Aragonite Saturation State of Surface Waters
(Orr et al 2005, Nature)

The extent of aragonite saturation controls the rate an organism such as a reef forming coral can build its skeletons or shells.

Present and Future Global Aragonite Saturation States ……

Year 2000

- Overall decline in aragonite saturation in the global ocean
- Polar and subpolar waters become undersaturated (corrosive)
Coral Reef calcification
- 1765 Adequate
- 2000 Marginal
- 2100 Low

Calcification rates in the tropics may decrease by 30% over the next century.

Projections of Aragonite Saturation Levels With Locations of Corals

Corals like warm, sunlit waters saturated in aragonite


In a future ocean Calcification < Erosion
- very serious for reef ecosystems as we know them
But Global Ocean Models Have Limitations Around:

- Continental margins
- Enclosed or semi-enclosed seas
- Arctic Sea
- Upwellings
- Shelf Seas and coastal waters

New research indicating that:

- Labrador Sea – low saturated waters from above and below
- Arctic Ocean also vulnerable to undersaturation

Aragonite Saturation State of Surface Waters
(Orr et al 2005, Nature)
Seasonal Invasion of Corrosive Waters on West Coast North America

Inflow of corrosive waters across shelf and over extensive, productive ecosystems

Upwelling of undersaturated waters ($\Omega_{\text{arag}}$ values $< 1.0$) onto shelf seas

ASH ($\Omega_{\text{arag}}$ values $= 1.0$) shoaling: 1m/a

Intermediate CO$_2$ rich corrosive waters ($\Omega_{\text{arag}}$ values $< 1.0$)

Schematic by C. Turley

Feely et al. Science (2008)
Upward Movement of Deep CO$_2$ Rich Corrosive Water

Non-corrosive waters $\Omega_{\text{arag}}$ values $< 1.0$)

ASH ($\Omega_{\text{arag}}$ values $= 1.0$) shoaling: 1-2 m/α

$\text{CO}_2$ rich corrosive waters ($\Omega_{\text{arag}}$ values $< 1.0$)

In Iceland Sea ~1km$^2$ of seafloor and seabed dwelling organisms exposed to corrosive waters each day due to shoaling of the ASH (Moy 2008)

70% Cold water corals will be in corrosive waters by 2100 (BAU scenario) (Guinotte et al. 2006). Fish use the coral thickets as a feeding ground and for shelter.

Schematic by C. Turley
Effects on Other Calcareous Seabed Dwelling Invertebrates

• Some species more sensitive to others
• Differences found in one species of oysters in Australia – so there may be some gene strains more resistant – new area of research

➢ Increasing CO₂ results in slower growth and lower final weight,
➢ These are adults but what about spats and juveniles, recruitment and settlement?

Gazeau 2007

Net calcification (μmol CaCO₃ g FW⁻¹ h⁻¹)

\[ r^2 = 0.70, P < 0.0001 \]

\[ r^2 = 0.55, P < 0.0001 \]

pCO₂ (ppmv)
Key Survival Processes in the Life Cycle and Physiology of an Organism

- **Energy Input**
- **Feeding**
- **Metabolism**
  - O₂ uptake
- **Maintenance Energy**
- **Organism**
- **Energy for Outputs**
  - Recruitment
  - Trade-offs & metabolic depression
  - Egg size & condition
  - Growth
  - Calcification
  - Reproduction

Schematic adapted by C Turley from H Wood (PML)
Examining the Full Life Cycle to Find the Weakest Link

- Some early life stages are very sensitive to ocean acidification
- Impacts vary with species
- Some more tolerant than others
### Experiments on Major Planktonic Calcifiers

<table>
<thead>
<tr>
<th></th>
<th># Extant species</th>
<th>Mineral form</th>
<th>Generation time</th>
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</thead>
<tbody>
<tr>
<td>Coccolithophores</td>
<td>~ 250</td>
<td>calcite</td>
<td>days</td>
</tr>
<tr>
<td>(autotrophs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foraminifera</td>
<td>~ 50</td>
<td>calcite</td>
<td>weeks</td>
</tr>
<tr>
<td>(heterotrophs)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euthecosomatous Pteropods</td>
<td>~ 32</td>
<td>aragonite</td>
<td>months to year?</td>
</tr>
<tr>
<td>(heterotrophs)</td>
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</tbody>
</table>

- CO₂ sensitivity experiments limited to a few species
- Majority show decrease in calcification – but not all – we need to understand if this is “real” or artefacts of different experimental design
Will Understanding the Mechanisms of Calcification Help us Understand Varied Response to CO$_2$?

Calcifiers are Living Organisms Protected by Membrane – so why worry?

- They have different mechanisms to control the pH of the microenvironment of calcification
- But despite this the majority show sensitivity to lower pH or carbonate ion concentration
- The mechanisms are different and may help explain the variation seen in lab experiments
- Understanding the generic mechanisms of calcification in the different groups of calcifiers may help us predict future responses to ocean acidification
Controlled Laboratory Experiments....

• Mainly short term experiments on single species

• Longer, multi-generation experiments now emerging but show no adaptation to high CO$_2$ after 150 generations

• Multiple species experiments showing complex interactions

• How do we interpret these for the real world of the oceans?
CO$_2$ Vents: “Windows” into a Future High CO$_2$ Ocean

Studies in the shallow waters of the Mediterranean and deep-sea CO$_2$ vents may help assess future ecosystem level impacts? Preliminary studies show:

- total loss of some species (supporting lab. experiments)
- reduced biodiversity
- “regime shifts” to totally different ecosystems

E.g. Sea grass benefit but so do invasive species

Will there be more jellyfish and Harmful Algal Blooms? We don’t know yet.
Windows into High CO₂ Ocean

- Natural CO₂ Vents at ambient temperature (shallow and deep ocean)
- Regions with naturally gradients from low to high CO₂ e.g. Baltic Sea, Benguela upwelling, E. tropical Pacific
- These regions generally show change in biota, especially calcifiers and other CO₂ sensitive species with changing pH, erosion>calcification
- May be useful future natural laboratories
Our Oceans and Seas Are Already Warming ……

Sea-surface temperature offshore Plymouth 1905-2000

Data source: Met Office Hadley Centre
Grid square 50-51°N, 4-5°W

Mean annual SST (°C)

11.0 11.5 12.0 12.5 13.0 13.5

Year

1905 1925 1945 1965 1985 2005

Our Oceans and Seas Are Already Warming ……

Global ocean

IPCC 2007
Combined Impacts of ocean Acidification and Warming of Oceans

Emerging evidence of enhanced combined impact of higher temperature and higher CO$_2$ on:

- Pteropod calcification
- Sea urchin gonad development
- Coral reef calcification 50% slower
- Barnacles (growth and settlement)

- Temperature thresholds for animals ("thermal window") shrinks in a high CO$_2$ ocean e.g. thermal stress elevated at higher CO$_2$ in crabs

- Changes in geographic distribution of predators and prey - poleward migration: regime shifts due to warming waters
Marine Food Webs - Highly Complex

• Every species lost causes a faster unravelling of the overall ecosystem

• So impacts of ocean acidification and temperature on fisheries can be indirect

• We are likely to see changes to ecosystems but predicting what future ecosystems look like and whether they will carry out the same roles is difficult

• Collapse of many fisheries associated with higher temperature (as well as over fishing)

• Ocean acidification is another stressor on already stressed fish stocks

California Current Food Web
Field and Francis 2004
Will Ocean Productivity Increase due to Warming? Predictions are ....

Will this be passed on to higher trophic levels?  Will this draw down more CO$_2$ or less?
Interactions between Ocean Acidification and Climate …….. Possible Important Feedbacks?

- **CO₂**
  - Wind strength

- **Ocean Acidification**
  - Loss of calcifiers
  - Iron availability
  - Nitrogen cycle
  - Carbon cycle - carbon removal to deep ocean

- **Climate Change**
  - Capacity of the ocean to take up CO₂ is slowing down
  - Biologically produced atmosphere changing gases

- **Warming**
  - Ocean productivity and diversity
  - Ocean physics – upwelling, fresh water input

- **Less oxygen – more “dead zones”**
Concern for Many Marine Organisms and Ecosystems ..........

- Reduced calcification rates
- Reduced growth, production and life span of adults, juveniles & larvae
- Reduced tolerance to other environmental fluctuations
- Combined impacts of ocean acidification and warming seas
- Changes to fitness and survival
- Changes to species biogeography
- Changes to biodiversity
- Changes to food webs
- Changes to ecosystem & their services
- Changes to feedbacks between ocean acidification and climate change and vice versa
- Uncertainties great – research required

C. Turley
A Noisier Future Ocean at Low pH?

• Sound absorption in low frequencies (where mammals communicate) will decrease in a high CO$_2$ ocean

• Sound will be higher and travel further

• Theoretical prediction - new issue just emerged and needs to be investigated e.g.:

  - on shipping noise

  - mammal communication

Hester et al. (2008) GRL
Sunset Over an Ocean with Man’s Footprint Now Detectable – Warmer, More Acidic, Less Diverse and Over Exploited

Oceans will become more acidic – very high certainty.

The Oceans are sick and it could be serious. It needs our help!

The only way of reducing the impact of global ocean acidification is a substantial and urgent reduction in CO\textsubscript{2} emissions – very high certainty.

Mitigation will make a difference – ocean acidification argues for stabilizing CO\textsubscript{2} lower than 450 ppm