Sentinel studies of ocean acidification in the Arctic Ocean and Japanese coasts

Naomi Harada¹, Katsunori Kimoto¹, Jun Kita², Jonaotaro Onodera¹, Masahiko Fujii³, Masahide Wakita¹, Tetsuichi Fujiki¹, Shintaro Takao⁴ and Tsuneo Ono⁵

¹ Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan.
² Marine Ecology Research Institute, Kashiwazaki, Japan
³ Hokkaido University, Sapporo, Japan
⁴ National Institute of Polar Research, Tachikawa, Japan
⁵ Japan Fisheries Research and Education Agency, Yokohama, Japan
What is ocean acidification?

$\text{H}^+ \text{ is described as “pH” which is defined as the decimal logarithm of the reciprocal of the hydrogen ion activity } a_{\text{H}^+} \text{ in a solution.}$
Aragonite saturation in 2100 (Ω aragonite)

Sub-Arctic and Polar Seas: Low CO$_3^{2-}$ brings low Ω

\[
Ω = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K'_{\text{sp}}}
\]

Saturation index (Ω)

- Ω>1: precipitation (shell preserved)
- Ω<1: undersaturation (shell dissolved)

\(K'_{\text{sp}}\): solubility product of calcite/aragonite
Observation sites at the Arctic Ocean and Japanese coasts

- Change in pH
- Response of typical organisms to OA (pteropods, abalone, sillago)

M1: Onjuku Station [Pacific side 1982 ~ ]
M2: Kashiwazaki Station [Japan Sea 1997 ~ ]
Seasonal change in subsurface pH of the western Arctic Ocean measured by glass electrode sensor (Kimoto Co. LTD)

Measurement timing is once a 60min. Resolution is 0.001pH and response speed is within 20 sec. Repeat accuracy is within ± 0.01pH (The 3rd winner of Accuracy Prize, XPRIZE competition). All data is calibrated after observation.

- Remnant and newly ventilated Pacific Winter waters (having relatively low but different pH values) are intricately laminated between 50-150m water depth.
- Common trend1: Relatively low winter and relatively high summer
- Common trend2: Minimum pH values during summer and the beginning of sea-ice season
Measurement of pteropods carbonate density by micro focus X-ray Computing Tomography method

Micro X-CT (MXCT)

Scan

Reconstruct

a. Specimen

b. Standard material (Calcite)
Calcite CT Number as a shell density index
relative value of X-ray attenuation coefficient in each voxels

\[
\text{Calcite CT Number} = \frac{\mu_{\text{sample}} - \mu_{\text{air}}}{\mu_{\text{calcite}} - \mu_{\text{air}}} \times 1000
\]

\(\mu_{\text{sample}}\): X-ray attenuation coefficient of samples
\(\mu_{\text{air}}\): X-ray attenuation coefficient of the surrounding air = -1000
\(\mu_{\text{calcite}}\): X-ray attenuation coefficient of calcite (standard material: Calcite or Aragonite) = 1000

Mean CT number vs Shell density

Kimoto et al., in prep
Precise shell density analysis of Sea butterfly (*Limacina helicina*, Thecosomatous pteropod)

**Transparent image**
(spatial resolution: 0.5 um)

**Distribution of Shell density**
(Unit: ug/um³)
Seasonal change in shell density of Arctic *L. helicina*

- **Mean CT number**
  - Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
  - Max 40% decrease

- **Sea ice melting**
- **Local corrosive condition produced by diagenesis of organic compounds**

- **Shallower trap average**
- **Dissolved**

- **Kimoto et al. in prep**
Changes in pH at Onjuku St, Pacific side and Kashiwazaki St, Japan Sea side

**Onjuku St. (Pacific coast 1982~)**
-0.007 / yr

**Kashiwazaki St. (Japan Sea coast 1997~)**
-0.011 / yr (Mar 2012 – Dec 2017)

Seawater inlet (350m offshore, 11m depth)
Intake quantity (75 m³/hour)

Shut-off of all reactors
### Annual change in pH
Comparison between pelagic and Japanese coastal zones

<table>
<thead>
<tr>
<th>Time series</th>
<th>pH (yr⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATS</td>
<td>-0.0017 ± 0.0001</td>
<td>Bates et al., 2014</td>
</tr>
<tr>
<td>ESTOC</td>
<td>-0.0014 ± 0.0001</td>
<td>Bates et al., 2014; González-Dávila et al., 2010</td>
</tr>
<tr>
<td>HOT</td>
<td>-0.0017 ± 0.0001</td>
<td>Bates et al., 2014; Dore et al., 2009</td>
</tr>
<tr>
<td>CARIACO</td>
<td>-0.0024 ± 0.0003</td>
<td>Bates et al., 2014; Astor et al., 2013</td>
</tr>
<tr>
<td>DYFAMED</td>
<td>-0.0019 ± 0.0009</td>
<td>Touratier and Goyet, 2011</td>
</tr>
<tr>
<td>MUNDA</td>
<td>-0.0016 ± 0.0003</td>
<td>Bates et al., 2014; Currie et al., 2011</td>
</tr>
<tr>
<td>KNOT/K2</td>
<td>-0.0024 ± 0.0007</td>
<td>Wakita et al., 2013</td>
</tr>
<tr>
<td>Station P</td>
<td>-</td>
<td>Wong et al., 2010</td>
</tr>
<tr>
<td>ONJUKU</td>
<td>-0.007</td>
<td></td>
</tr>
<tr>
<td>KASHIWAZAKI</td>
<td>-0.011</td>
<td></td>
</tr>
</tbody>
</table>

E section at 10° N

*calculated from T, S, Nutrients, DIC and TA
Effects of diurnally-fluctuating $pCO_2$ on ezo-abalone larvae by rearing experiment

Constant treatments
Targeted $pCO_2$
400 µatm, 800 µatm, 1200 µatm

Results of monitoring (Dotted lines)
430 ± 15, 732 ± 19, 1175 ± 20 µatm

Diel cycle treatments
Targeted $pCO_2$
400-1200 µatm, 800-1600 µatm

Results of monitoring (Solid lines)
420-1189 µatm, 739-1537 µatm

Results: Effects on ezo-abalone larval fitness

Slightly high: 400-1200, 800, 800-1600 µatm

Significantly high: 1200 µatm and 800-1600 µatm

Significantly short: 800-1600 µatm

Results 2: Effect of “integral $p\text{CO}_2$” on larval fitness

- Malformation rate increased around 1.1 of $\Omega_{\text{ara}}$ which corresponds to $\approx 1100$ µatm of $p\text{CO}_2$.

- The impacts of OA on growth of larval abalone can be determined by intensity and time of exposure to $p\text{CO}_2$ over the threshold called as “Integral $p\text{CO}_2$ over 1100 µatm”.

- Integral $p\text{CO}_2$ over 1100 µatm

$$\sum (P - 1100)i$$

$P$: $p\text{CO}_2$ over 1100 µatm
$i$: exposed hours to $p\text{CO}_2$ over 1100 µatm

- Larval shell length decreased with the increasing of integral $p\text{CO}_2$ over 1100 µatm.

**Sillago japonica**

Model marine-fish for pollutant contamination tests

Maximum Size: 30 cm

Range: Temperate zone of Japanese coast

Important fish for fisheries industry
Early life development of *S. japonica*

- Egg diameter ca. 700 μm
- 1 day after hatch, TL 2.7 mm
- 3 days after hatch, TL 3.0 mm
- 8 days after hatch, TL 4.5 mm
- 15 days after hatch, TL 8.0 mm
- 38 days after hatch, TL 30 mm
Rearing system for larval *S. japonica*

Phytoplankton: *Tetraselmis tetrathele* and *Pavlova lutheri*

Zooplankton: *Branchionus plicatilis* sp. complex

Fish rearing tank
Temp: 26°C
Sal: 32.5
Total alkalinity: 2250μmol/kgsw
Rearing experiments of larval *S. japonica* with different pH condition

Tank 1:
Initial pH: 8.09
Without pH control during experiment

Tank 2:
Initial pH: 8.15
Without pH control during experiment

Tank 3:
Initial pH: 8.13
With slightly pH controlled using water passed through the pH modifying tank by aeration to make $pCO_2$ equal to $pCO_{2air}$

Tank 4:
Initial pH: 8.13
With slightly pH controlled using water passed through the pH modifying tank by aeration to make $pCO_2$ equal to $pCO_{2air}$

Inflow with pH 8.05 ($pCO_2$ 580 μatm) → pH modifying tank → Outflow pH 8.18 ($pCO_2$ 400 μatm)
Impacts of change in pH on larval *S. japonica*

- **pH changes during rearing and survival rate at 8 days**
  - Days after hatch vs #8 pH
  - Days after hatch vs #9-1 pH
  - Days after hatch vs #9-3 pH
  - Days after hatch vs 2016 pH

Note: pH is that of inflow water of tank (water inside the tank was not taken for pH monitor because the larval *S. japonica* is very delicate)

"Threshold" is also important for juvenile's survival of *Sillago japonica*?
Summary

• Subsurface pH in the western Arctic Ocean observed from Sep 2015 to Sep 2016 showed large seasonality with dynamic range of 0.5 pH unit. The pH largely dropped in summer and the beginning of sea-ice seasons.

• Pteropods shell density decreased maximum 40% responding to the reduction of aragonite saturation degree ($\Omega_{\text{ara}}$) during summer and the beginning of sea-ice seasons in the western Arctic Ocean.

• At Japanese coastal stations, the annual pH reduction rate was -0.007 and -0.011 at the Pacific and Japan Sea sides, respectively. These are twice or three times larger than those of monitoring sites in pelagic oceans.

• Popular commercial organisms, ezo-abalone and *Sillago japonica* responded to ocean acidification. Rearing experiments showed that their juvenile received immediately negative impact when the pH (or $\Omega_{\text{ara}}$ or $p\text{CO}_2$) drops under the threshold.

• Adaptation strategies for marine organisms such as seed production of commercially important fish are necessary to overcome progress in future ocean acidification.