A biological contribution to partial pressure of CO$_2$ in the western Arctic Ocean and Bering Sea

*Futsuki, R.*, T. Hirawake$^2$, A. Fujiwara$^{2,3}$, T. Kikuchi$^4$, S. Nishino$^4$, D. Sasano$^{5,6}$, M. Ishii$^{5,6}$, H. Uchida$^4$ and S. Saitoh$^2$

*E-mail: futsuki@salmon.fish.hokudai.ac.jp

$^1$Graduate School of Fisheries Sciences, Hokkaido University,
$^2$Faculty of Fisheries Sciences, Hokkaido University,
$^3$Arctic Environment Research Center, National Institute of Polar Research,
$^4$Research and Development Center for Global Change, JAMSTEC,
$^5$Global Environment and Marine Department, Japan Meteorological Agency,
$^6$Oceanography and Geochemistry Research Department, Meteorological Research Institute

S9: Variability in advection and its biological consequences for Subarctic and Arctic ecosystems

PICES Annual Meeting 2014
Oct. 16-26, Yeosu, Korea
The ocean plays a crucial role in mitigating effects of perturbation to the climate system, sequestering 20 to 35% of anthropogenic CO\textsubscript{2} emissions (Khatiwala et al., 2009)

**<Arctic Ocean>**

Total sink of atmospheric CO\textsubscript{2} : 65-175 TgC yr\textsuperscript{-1}

- Contributing 5-14% to the global ocean’s net uptake of CO\textsubscript{2} (Takahashi et al., 2002, 2009; Bates and Mathis, 2009)

Especially...

Chukchi Sea is a large ocean sink for CO\textsubscript{2} briefly in summer, sea ice-free period and contributes nearly 1/3 to 1/2 of the CO\textsubscript{2} sink in the Arctic (Bates et al., 2011a)

**<Bering Sea>**

Bering sea shelf shift from neutral CO\textsubscript{2} sink/source status in spring to strong oceanic sink for CO\textsubscript{2} by summer (Bates et al., 2011a)
Partial pressure of $\text{CO}_2$ ($\rho\text{CO}_2$) vary with

1) Solubility change (temperature, salinity) → solubility pump
2) Vertical mixing (wind-induced, sea ice formation) → physical pump
3) Gas exchange at sea surface
4) Advection of other water masses and fresh water inflow
5) Phytoplankton uptake → biological pump

Seasonally significant
Recent Arctic environment

- Increase in flesh and heat water flux depends on increasing Bering Strait throughflow (Woodgate et al., 2012)
- Reduction of sea ice area in summer and earlier retreat of sea ice
- Shift in timing of phytoplankton bloom and change in annual primary production (e.g. Brown and Arrigo, 2012; Ji et al., 2013, etc...)

Rapid environmental change in the Arctic Ocean

The Arctic marine carbon cycle will likely enter a high dynamic state in coming decades, with large uncertainties in the exchange of atmosphere-ocean CO₂ (Bates et al., 2011b)
There are many researches focusing on relationship between $p\text{CO}_2$ and physical processes
Ex) Murata and Takizawa, 2003; Hauri et al., 2013, etc...

However

Few studies have focused on relationship between $p\text{CO}_2$ and biological processes
⇒ Thus, little is known about how much biological processes affect $p\text{CO}_2$

It’s important to clarify the biological contribution to $p\text{CO}_2$ for more understanding of air-sea CO$_2$ flux in the western Arctic and Bering Sea where environmental change is rapid
• To clarify biological contribution to $pCO_2$ in the western Arctic and Bering Sea
Materials & methods

In-situ and satellite data

**Cruise data**
R/V “Mirai” Arctic Cruise, 2012 (MR12-E03)
3rd Sep. – 17th Oct., 2012

**In-situ and satellite data**

- Partial pressure of CO$_2$ ($p$CO$_2$)
- Sea Surface Temperature (SST)
- Sea Surface Salinity (SSS)
- Chlorophyll a concentration (Chl.a)
- Mean wind speed
- Open water period

**Physical**
- Mean primary productivity

**Biological**
- Total Alkalinity (TA), Salinity (Sal), Dissolved Inorganic Carbon (DIC)

→ CTD bottle sampling data
**Materials & methods**

**Data sampling and processing**

*pCO$_2$ [μatm], SSS [psu], SST [°C] and Chl-a [mg m$^{-3}$]*

1$^{st}$ step: Seawater was pumped up from 4.5m below the sea surface.

*pCO$_2$: Cavity Ring-Down Spectroscopy (CRDS), and SSS; SST; Chl.a: Continuous sea surface water monitoring system*

**Open water period (OP) [days]**

Satellite derived sea ice concentration (SIC), SSMI/DMSP, 25km, Daily

The period from onset of ice retreat to observed day → The day that SIC is first below 10%

**Primary Productivity [mg C m$^{-2}$ d$^{-1}$]**

Satellite derived $a_{ph}(443)$, $E_0$, $Z_{eu}$, MODIS/Aqua, 9km, Daily

Calculated by the algorithm using phytoplankton light absorption coefficient ($a_{ph}(\lambda)$) (Hirawake et al., 2011) and optimized by a parameter in Arctic region

**Wind speed [m s$^{-1}$]**

NCEP/North American Regional Reanalysis (NARR), Wind speed at 10m above sea level, 32km 3 hours
Materials & methods

Cluster analysis

$pCO_2$ & environmental parameters

- SST
- SSS
- Chl.a

Open water period (OP)
Mean wind speed during OP
Mean primary productivity during OP
$\Delta pCO_2 (pCO_2\text{sea} - pCO_2\text{air})$

Normalized: $\frac{(X - \bar{X})}{\sigma}$

Classified into 6 regions

1. Bering sea basin
2. Northern Bering & central Chukchi Sea
3. Northern shelf of Chukchi Sea
4. Southern Chukchi Sea
5. Southern Bering Strait
6. Northern Chukchi Sea (basin & slope)
Materials & methods

Estimation method of biological contribution

Water mass analysis

\[
\begin{align*}
    f_{\text{Bering}} + f_{\text{River}} + f_{\text{Ice}} &= 1 \\
    f_{\text{Bering}} S_{\text{Bering}} + f_{\text{River}} S_{\text{River}} + f_{\text{Ice}} S_{\text{Ice}} &= S \\
    f_{\text{Bering}} T A_{\text{Bering}} + f_{\text{River}} T A_{\text{River}} + f_{\text{Ice}} T A_{\text{Ice}} &= T A
\end{align*}
\]

※This analysis is not available in south of Bering Strait due to no CTD sampling data

<table>
<thead>
<tr>
<th>End-member</th>
<th>End-member value</th>
<th>(Cai et al., 2010)</th>
<th>Sal. [psu]</th>
<th>TA [µmol kg(^{-1})]</th>
<th>DIC [µmol kg(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bering Sea water</td>
<td></td>
<td></td>
<td>33.218</td>
<td>2257.9</td>
<td>2161</td>
</tr>
<tr>
<td>River water</td>
<td></td>
<td></td>
<td>0</td>
<td>1100</td>
<td>1150</td>
</tr>
<tr>
<td>Sea ice melt water</td>
<td></td>
<td></td>
<td>5</td>
<td>450</td>
<td>400</td>
</tr>
</tbody>
</table>

evaluated 3-component fraction of end-members \( (f_{\text{Bering}}, f_{\text{River}}, f_{\text{Ice}}) \)
Results & Discussion

Spatial distribution of $\Delta p\text{CO}_2$

- Most regions had CO$_2$ sink condition except southern Bering strait
- Spatial variability of $\Delta p\text{CO}_2$ was significant (-200 < $\Delta p\text{CO}_2$ < 160)

![Graph showing spatial distribution of $\Delta p\text{CO}_2$](image)

**Significant CO$_2$ sink condition**

**CO$_2$ source condition**

**Neutral CO$_2$ sink/source condition**

$\Delta p\text{CO}_2$ (μatm)
Results & Discussion

Biological contribution

- Northern & central shelf of Chukchi Sea (Cluster 2, 3)
  ⇒ Large biological contribution: 47%(2.6), 39%(8)
- Southern Chukchi Sea (Cluster 4)
  ⇒ Not so large biological contribution: 20%(24)
- Southern Bering Strait and northern Chukchi Sea (Cluster 5, 6)
  ⇒ No biological contribution: 1%(39), 0%(12)

CO$_2$ release via organic carbon respiration

CO$_2$ uptake

CO$_2$ release via organic carbon respiration

Expected DIC (μmol kg$^{-1}$)

Biological drawdown

In-situ pCO$_2$ [μatm]

Cluster

Biological drawdown

Expected pCO$_2$ [μatm]
Significant low $\Delta p\text{CO}_2$ region

2. Northern Bering & central Chukchi Sea
   $\Rightarrow \Delta p\text{CO}_2 : -131(39) \text{ μatm}, 47%$
   - Relatively high mean primary productivity (702 mg C m$^{-2}$ d$^{-1}$)
   - Relatively weak wind (5.55 m s$^{-1}$)
   - Less stratification ($f_{\text{sim}} = 1\%$)

3. Northern shelf of Chukchi Sea
   $\Rightarrow \Delta p\text{CO}_2 : -109(39) \text{ μatm}, 39%$
   - Relatively high Chl.a (0.9 mg m$^{-3}$)
   - Relatively weak wind (5.04 m s$^{-1}$)
   - Less stratification ($f_{\text{sim}} = 8\%$)

In-situ biological pump and/or advection of low $p\text{CO}_2$ water after blooming allowed significant $\text{CO}_2$ sink condition in these regions

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Chl.a Median(IQR)</th>
<th>mean_PP Median(IQR)</th>
<th>mean_wind Median(IQR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster1</td>
<td>0.60(0.44)</td>
<td>605(94)</td>
<td>7.33(0.21)</td>
</tr>
<tr>
<td>Cluster2</td>
<td>0.53(0.50)</td>
<td>702(155)</td>
<td>5.55(0.60)</td>
</tr>
<tr>
<td>Cluster3</td>
<td><strong>0.90(0.50)</strong></td>
<td>450(124)</td>
<td>5.04(0.55)</td>
</tr>
<tr>
<td>Cluster4</td>
<td>1.40(0.95)</td>
<td>807(67)</td>
<td>6.46(0.29)</td>
</tr>
<tr>
<td>Cluster5</td>
<td>0.55(0.43)</td>
<td>624(139)</td>
<td>5.59(0.45)</td>
</tr>
<tr>
<td>Cluster6</td>
<td>0.09(0.04)</td>
<td>382(170)</td>
<td>5.52(0.34)</td>
</tr>
</tbody>
</table>
Neutral $\Delta pCO_2$ region

4 Southern Chukchi Sea
⇒ $\Delta pCO_2 : -57(33) \mu$atm, 20%
- High primary productivity (807 mg C m$^{-2}$ d$^{-1}$)
- High chl.a (1.40 mg m$^{-3}$)
+ Significant stratification by sea ice melt water ($f_{SIM} = 10\%$)
+ Relatively strong wind (6.46 m s$^{-1}$)

6 Northern Chukchi Sea
⇒ $\Delta pCO_2 : -23(13) \mu$atm, -1%
± Low primary productivity (382 mg C m$^{-2}$ d$^{-1}$)
± Low Chl.a (0.09 mg m$^{-3}$)
+ Significant stratification by sea ice melt water ($f_{SIM} = 16\%$)

Shallow mixed layer depth and strong stratification by sea ice melted-water allowed relatively quick re-equilibration with atmosphere (Cai et al., 2010)
Conclusion

- The northern Bering, central & northern shelf of Chukchi Sea (Cluster 2, 3) had significant CO₂ sink condition and biological CO₂ uptake largely contributed to $p_{CO₂}$.
- The southern & northern Chukchi Sea (Cluster 4, 6) where strongly stratified by sea ice melt water had relatively neutral CO₂ sink/source condition, and biological contribution to $p_{CO₂}$ was not so large or nothing.
If further sea ice reduction and earlier ice retreat will occur (e.g. IPCC AR5; Brown and Arrigo, 2012), and annual net primary productivity will increase (e.g. Arrigo et al, 2008; Pabi et al, 2008); two possible scenarios are expected:

- CO$_2$ sink will be enhanced in the region where primary productivity increase

- Strong and broad stratification may occur by further sea ice reduction and earlier ice retreat, and allow relatively quick re-equilibration with atmosphere and prevent CO$_2$ uptake from atmosphere to the ocean.
Thank you
for your attention