Transient tracers in the Fram Strait – Excess SF$_6$ and anthropogenic carbon transport

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Transient tracers

General
• CFCs, SF$_6$, Ar$^{39}$
• inert trace gases
• enter ocean via gas-exchange only
• provide time information (atmospheric history / input function)

OUTPUT
• mean age
• changes in ventilation
• ventilation pattern
• anthropogenic carbon
• AOUR
The Inverse Gaussian – Transit Time Distribution

\[ C(t_s) = \int_{0}^{\infty} C_0(t_s - t) \exp(-\lambda t) \cdot G(t) dt \]

\[ G(t) = \frac{\Gamma^3}{\sqrt{4\pi \Delta^2 t^3}} \cdot \exp\left(\frac{-\Gamma(t - \Gamma)^2}{4\Delta^2 t}\right) \]

- IG-TTD is based on constant adv./dif. along flow pathway
- parameters to constrain: \( \Gamma = \text{mean age} / \Delta = \text{width of the IG-TTD} \)
- transient tracer couples \( \rightarrow \) sufficiently different input functions
- tracer age / apparent age is based on a purely advective flow
- tracer age used as tracer unit instead of concentrations
Transient tracers at 79°N

- ARK-XXVII/1 expedition in 2012
- Measurements of CFC-12 and SF$_6$ along 78°50′N (red) and along the fast ice edge (blue)
- Data publically available at CDIAC (CLIVAR Repeat Section 75°N)
Transient tracers at 79°N

\[ \Delta / \Gamma = 1.0 \]

![Graphs showing pressure vs. longitude and tracer age relationships](image-url)
Saturation models

- saturation model extremely biased at high latitudes
- good agreement in tropical / subtropical regions
- saturation in the Greenland Sea as proxy for the water masses in the Fram Strait
Tracer release experiment

- tracer release experiment in the central Greenland Sea in 1996
- 300 kg of SF$_6$
- distribution pattern in 2012?

A.J. Watson et al., Letters to nature 1999
Supersaturation by bubble effects

- less soluble gases like \( \text{SF}_6 \) are much more affected by bubble effects
- data observations during heavy wind conditions are relatively rare
- high uncertainties of the models

Excess $\text{SF}_6$

Assumptions

- IG-TTD valid with $\Delta/\Gamma = 1.0$
- CFC-12 time dependent undersaturation (Shao et al., JGR 2013; Tanhua et al., JGR 2008)

CFC-12 (corrected) $\rightarrow \Gamma \rightarrow \text{SF}_6$ (theoretical)
$\text{SF}_6$ (excess) = $\text{SF}_6$ (measured) $– \text{SF}_6$ (theoretical)
Mean age and anthropogenic carbon

- $C_{\text{ant}}$ as inert tracer / „transient tracer“
- Boundary condition:
  \[
  \begin{align*}
  pCO_2,\text{preind} + TA_{\text{pref}} & \rightarrow DIC_{\text{preind}} \\
  pCO_2,\text{hist} + TA_{\text{pref}} & \rightarrow DIC_{\text{hist}} \\
  DIC_{\text{hist}} - DIC_{\text{preind}} & = C_{\text{ant}}(0)
  \end{align*}
  \]
- $C_{\text{ant}}(0) + IG-\text{TTD} \rightarrow \text{interior } C_{\text{ant}}(t) + \Gamma$
Arctic Ocean mass balance

- $C_{\text{ant}}$ concentrations are highest in poleward flowing water masses in the Fram Strait, Bering Strait and Barent Sea Opening.
- $C_{\text{ant}}$ concentrations in poleward flowing WM increase twice as fast as in equatorward flowing WM (~2 $\mu$mol/kg yr between 2002 and 2012).
- Canadian Archipelago?

<table>
<thead>
<tr>
<th>Water mass</th>
<th>$C_{\text{ant}}$ ($\mu$mol kg$^{-1}$)</th>
<th>Mean age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AW/RAW</td>
<td>50 ($\pm$6)</td>
<td>9 ($\pm$10)</td>
</tr>
<tr>
<td>PSWw</td>
<td>46 ($\pm$5)</td>
<td>9 ($\pm$10)</td>
</tr>
<tr>
<td>PSW</td>
<td>43 ($\pm$2)</td>
<td>7 ($\pm$6)</td>
</tr>
<tr>
<td>AAW</td>
<td>38 ($\pm$5)</td>
<td>32 ($\pm$15)</td>
</tr>
<tr>
<td>AIW</td>
<td>31 ($\pm$5)</td>
<td>54 ($\pm$20)</td>
</tr>
<tr>
<td>uPDW</td>
<td>28 ($\pm$4)</td>
<td>69 ($\pm$19)</td>
</tr>
<tr>
<td>NDW</td>
<td>18 ($\pm$4)</td>
<td>143 ($\pm$44)</td>
</tr>
<tr>
<td>CBDW</td>
<td>15 ($\pm$2)</td>
<td>173 ($\pm$23)</td>
</tr>
<tr>
<td>EBDW/GSDW</td>
<td>11 ($\pm$1)</td>
<td>254 ($\pm$32)</td>
</tr>
</tbody>
</table>
Transport through Fram Strait

- mean velocity field from 2002-2010
- separated into Polar Water, Atlantic Water and Recirculating/Return Atlantic Water
- flux data in the Fram Strait has high uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Volume (Sv)</th>
<th>Transport (Tg C yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DIC</td>
<td>Anthropogenic carbon</td>
</tr>
<tr>
<td>AW</td>
<td>4.4 (±3.2)</td>
<td>3592 (±2612)</td>
</tr>
<tr>
<td>RAW/AW</td>
<td>−3.5 (±1.9)</td>
<td>−2852 (±1549)</td>
</tr>
<tr>
<td>PW</td>
<td>−1.4 (±0.8)</td>
<td>−1118 (±639)</td>
</tr>
<tr>
<td>Σ</td>
<td>−0.5</td>
<td>−378</td>
</tr>
</tbody>
</table>

Outlook

- **Saturation at high latitudes**
  - bubble mediated gas transfer of transient tracers
  - comparison with existing models (Ne, Ar, He)
  - possible relationship between chem. / phys. parameters?
  - influence of ice cover / gas exchange

- **More refined ventilation models for high latitudes?**
Thank you!