**TσV analysis on watermass processes in the Sea of Okhotsk**

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  - Summer
  - Boundaries of Identified Element Watermasses
- Events in seasonal cycle:
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  - NE-SW density section and T/S diagram
- April Event:
  - Density surface $\sigma = 26.7$ topography and Tpt on it
  - NW-SE density section and T/S diagram
- Gyre and Pycnostad:
- Summary

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Scientific Question & Approach

- **Basic Question:** "Do we fully understand the ocean response to the seasonal cycle of atmospheric forcing, enough to predict future climate change?"

- **Scientific Question:** The Oyashio Water is one of the waters having **decadal cooling trend** in the world oceans. How do the watermass processes in the source region of Oyashio Water, *i.e.* the Sea of Okhotsk, respond to the seasonal cycle of atmospheric forcing?

- **Approach:** $T\sigma V$ analysis, using climatic monthly data base of WOA09, defining watermass as the **peaks of volume distribution** on $T\sigma V$ diagram bounded by pycnocline or physical boundaries;

  - **Specifications of $T\sigma V$ Analysis**

    1. Analyzed Data: WOA09 $1^\circ \times 1^\circ$ mesh monthly standard depth data of 182 stns in the Sea of Okhotsk;
    2. Digitized: $\Delta D = 10$ m; $\Delta T pt_0 = 0.5$ °C; $\Delta \sigma_0 = 0.1$ kg m$^{-3}$; $\Delta S = 0.1$ psu;
    3. Calculated parameters: volume of element watermass, volume-weighted-mean $T pt_0$, $\sigma_0$, $S$ of element watermass;
✓ **Black Contour & Color Pattern**: Winter Tpt on Sigma=26.7: representative density of NP Intermediate Water; by WOA09 data

✓ **White Contour**: Stream-line of Subarctic Gyre in Winter = Depth contour of Sigma=27.0 surface (= main pycnocline); by WOA09 data

☐ **Cooling of NPSAW occurs mainly in the Sea of Okhotsk**;
Winter $\sigma V$ diagram of the Sea of Okhotsk
Summer $T \sigma V$ diagram of the Sea of Okhotsk
## Boundaries of Identified Element Watermasses of the Sea of Okhotsk

<table>
<thead>
<tr>
<th>Watermass</th>
<th>$\sigma_0$</th>
<th>$T_{pt}$</th>
<th>Physical Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Btm</td>
<td>Top</td>
<td>Btm</td>
</tr>
<tr>
<td>SfW</td>
<td>$&lt;26.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SbzW</td>
<td>$26.4 \leq$</td>
<td>$&lt;-0.5$</td>
<td></td>
</tr>
<tr>
<td>IntW</td>
<td>$26.4 \leq$</td>
<td>$&lt;27.1$</td>
<td>$-0.5 \leq$</td>
</tr>
<tr>
<td>DpW</td>
<td>$27.1 \leq$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Events in seasonal cycle: Volume of Element Watermasses

**EKC Water**:  
- SfW disappear in Jan ~ Apr;  
- Boundary between IntW and DpW deepen in Oct and Jan ~ Apr;  
- No SbzW:

**OK Water**:  
- SfW exist all through the year;  
- SbzW start decrease in autumn and almost disappear in Nov and Dec, but almost recover in Jan;  
- Boundary between IntW and DpW deepen in Dec ~ Apr;

**OY Water**:  
- SfW disappear in Jan ~ Apr;  
- Boundary between IntW and DpW deepen in Dec;

- The disappearance of SfW in EKC and OY Water in Jan ~ Apr; can be caused by convection at the open water;

- The boundary between IntW and DpW is the surface of main pycnocline, and deepening of this surface is due to spin-up of NP-SAG, which is enhanced in the western boundary (Kashiwai, 2010);
**Events in the seasonal cycle: T/S of Element Watermasses (1)**

- **SfW:**
  - In **Jan**, T/S drops, when S increase with sea ice formation is expected;
  - In **Apr**, when already entered warming season, the temperature of SfW of OK Water show temporal minimum, (while salinity is almost unchanged);
  - This can be caused by mixing of SfW and SbzW occurs in April, and a part of mixed water supplied to SfW and cause temperature drop;
  - In **Nov**, the middle of cooling season, the salinity of SfW of EKC, OK and OY Water increase;
  - This can be caused by autumn cooling convection reaching to the boundary between SfW and IntW (SbzW) and start mixing between SfW and IntW;

- **SbzW (OK Water):**
  - In **Jan**, T/S drop:
    - Considering with volume recovery of in Jan, SbzW is produced in Jan;
    - Salinity drop can be caused by concurrent freezing/melting at sea ice development (Watanabe et al., 2004);
  - In **Apr**, salinity of SbzW shows temporal maximum, while temperature is almost unchanged;
  - Why, salinity maximum at sea ice melting month?
Events in the seasonal cycle: T/S of Element Watermasses (2)

**IntW**:  
✓ In EKC, OY Water, T/S drop from Jan, considering with corresponding disappearance of SfW, which indicate results of direct atmospheric cooling, and mixing with SfW;  
✓ While in OK Water, T drop is delayed by one month to Feb.  

- Possible reasons are:  
  - time for inflow of significant volume of cooled EKC Water;  
  - weaker atmospheric cooling due to extending ice cover;  
  - larger heat gain by mixing with warmer DpW;

**DpW**:  
✓ Comparing with other element watermass, seasonal changes of DpW are very small;
Events in the seasonal cycle: Surfacing of Element Watermasses

Number of stations where element watermasses are surfacing (WOA09 data, total stations in the Sea of Okhotsk=182).

<table>
<thead>
<tr>
<th>Month</th>
<th>SbzW</th>
<th>IntW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nov</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dec</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td>Jan</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>Feb</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>Mar</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td>Apr</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>May</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Jun</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

✔ SbzW surfaces in Apr;
✔ IntW surfaces from Dec to Mar;

☐ Why SbzW does not surface, while IntW does surface?
   * As shown later, SbzW distribute under the ice cover in the N~NW~W part of the Sea of Okhotsk;

☐ Why in April?
Density surface $\sigma = 26.7$: representative density of IntW;

**Topography: upper panel**
- The depression of density surface extends from NE to SW part of the Sea of Okhotsk, indicating clockwise local gyre, and the deepest part of 600m deep is in the NE part;
- The rise of this density surface exists around North Kuril Islands and rising up to 50m less, indicating very strong anti-clockwise local gyre;

**Tpt on $\sigma = 26.7$ surface: lower panel**
- The water of Tpt $\leq 0^\circ$C, i.e. SbzW, distribute only in the NW Shelf Region, where is under ice cover;
January Event: **NE-SW density section and T/S diagram**

✓ **NE-SW density section** (upper panel):  
  - **NE part** (right-hand side): The density contours of $\sigma = 26.2 \sim 26.5$ show broad depression, indicating clockwise local gyre. In this gyre, the isopycnals forming this depression are standing vertical (i.e. pycnostad);
  
  - **North Kuril Islands section** (central part): The isopycnal of $\sigma = 26.60 \sim 26.66$ is rising up to the surface of 20m deep less. The isopycnals are standing vertical (i.e. pycnostad) and indicating existence of strong anti-clockwise local gyre.

✓ **T/S diagram** (lower panel):  
  - The T/S diagram indicates that the pycnostad appearing in the local gyre are not well mixed water, but T/S compensating pycnostad.
April Event: Density surface $\sigma = 26.7$ topography and Tpt on it

In April:

✓ **Topography**: upper panel
  - IntW is surfacing in the NW part of the Sea of Okhotsk;
  - The rise of this density surface in the NW part indicate formation of the anti-clockwise local gyre;
  - The depression in the E part of the Sea of Okhotsk, indicates formation of clockwise local gyre;

✓ **Tpt**: lower panes
  - The water of Tpt $\leq 0$ C°, i.e. SbzW, distributes in the NW ~ W part, where the anti-clockwise gyre is formed;
Local Gyre and Pycnostad: signature of deep convection

Comparison of Winter Deep Convection Regions and the Sea of Okhotsk

<table>
<thead>
<tr>
<th>Preconditioning &amp; Driving factors</th>
<th>Region of Winter Deep Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gulf of Lion</td>
</tr>
<tr>
<td>Pycnostad</td>
<td></td>
</tr>
<tr>
<td>Circulation</td>
<td>Cyclonic</td>
</tr>
<tr>
<td>Strong wind</td>
<td></td>
</tr>
<tr>
<td>Strong cooling</td>
<td></td>
</tr>
<tr>
<td>Open water</td>
<td>No Seaice</td>
</tr>
<tr>
<td>Salinity supply</td>
<td>Mediterranean Water</td>
</tr>
<tr>
<td>Outcrop water</td>
<td>West Mediterranean Deep Water</td>
</tr>
</tbody>
</table>

(Revised from Kashiwai, 2009)

✓ In the Sea of Okhotsk, all the preconditioning factors and driving factors is working. Thus, we can expect the occurrence of deep convection in the Sea of Okhotsk, especially in January and April. Tidal mixing, and thin surface layer can enhance occurrence of deep convection.
Summary

1. TσV Analysis provided expected performance in identifying element watermasses in OK, EKC and OY Waters, separated by pycnocline;
   ✓ SfW, SbzW, IntW and DpW were identified;

2. Volume and volume-weighted-mean Tpt, and S of element watermasses were calculated, which indicates important features of watermass process in the Sea of Okhotsk;
   ✓ Monthly scale events dominate in seasonal cycle of watermass characteristics;
     □ Cooling by surfacing of element watermass and mixing through T/S compensating pycnostad, associated with local gyres, appear in Jan and Apr, which can be a signature of Deep Convection;
     □ In Jan Event, when volume of SbzW is recovered, T and S of SbzW both drops. This is possible by ice-cover development with concurrent freezing and melting, as shown in a numerical experiment (Watanabe et al., 2004);
     □ In Apr event, the SbzW salinity shows temporal maximum. This can be caused by mixing with DSW, which is dropped from coarse data interval of standard depths;
     □ Deepening of boundary between IntW and DpW occurs in Dec~Apr, which is the response of the main pycnocline of Subarctic NP to spin-up of Subarctic Gyre;