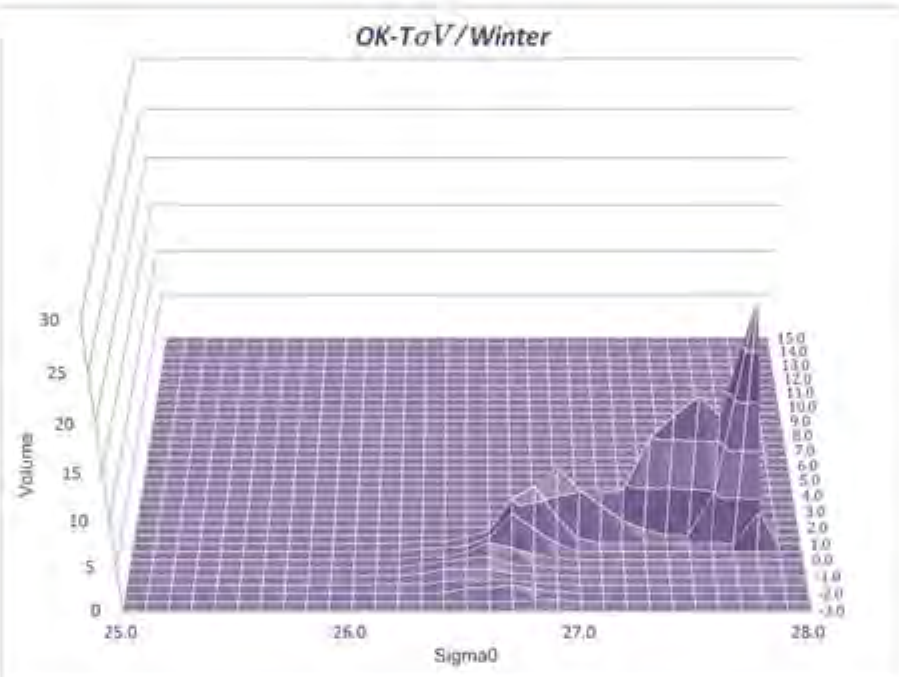
TσV analysis on watermass processes in the Sea of Okhotsk



(Fisheries Oceanography Research Studio "OyashioYa")
Makoto KASHIWAI

- Science question and approach;
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- TσV diagram;
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  - *Summer*
  - *Boundaries of Identified Element Watermasses*
- Events in seasonal cycle:
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  - *T/S*
- January Event:
  - *Density surface $\sigma = 26.7$ topography and Tpt on it*
  - *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

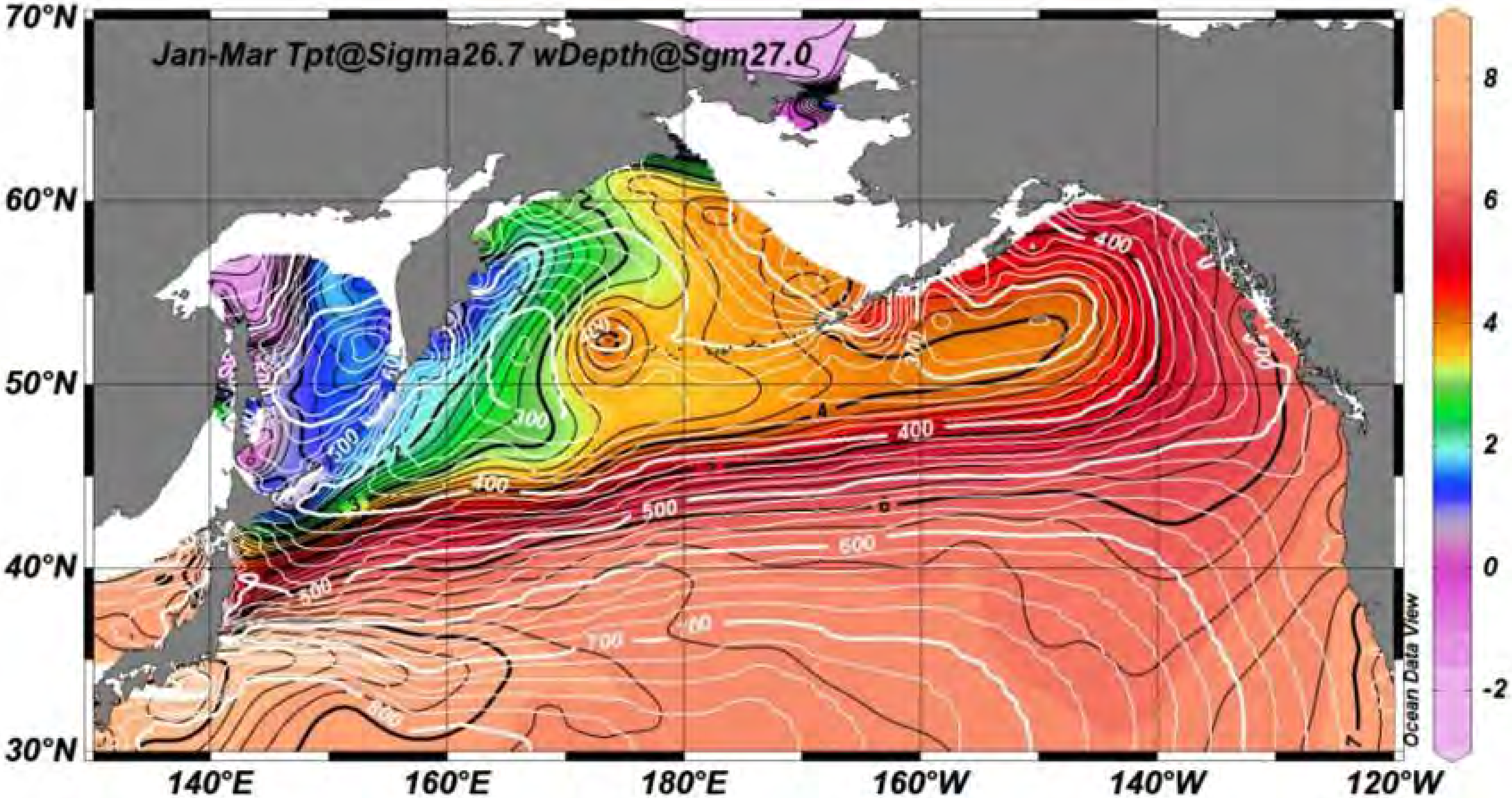
Scientific Question & Approach

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

  - *Specifications of TσV Analysis*

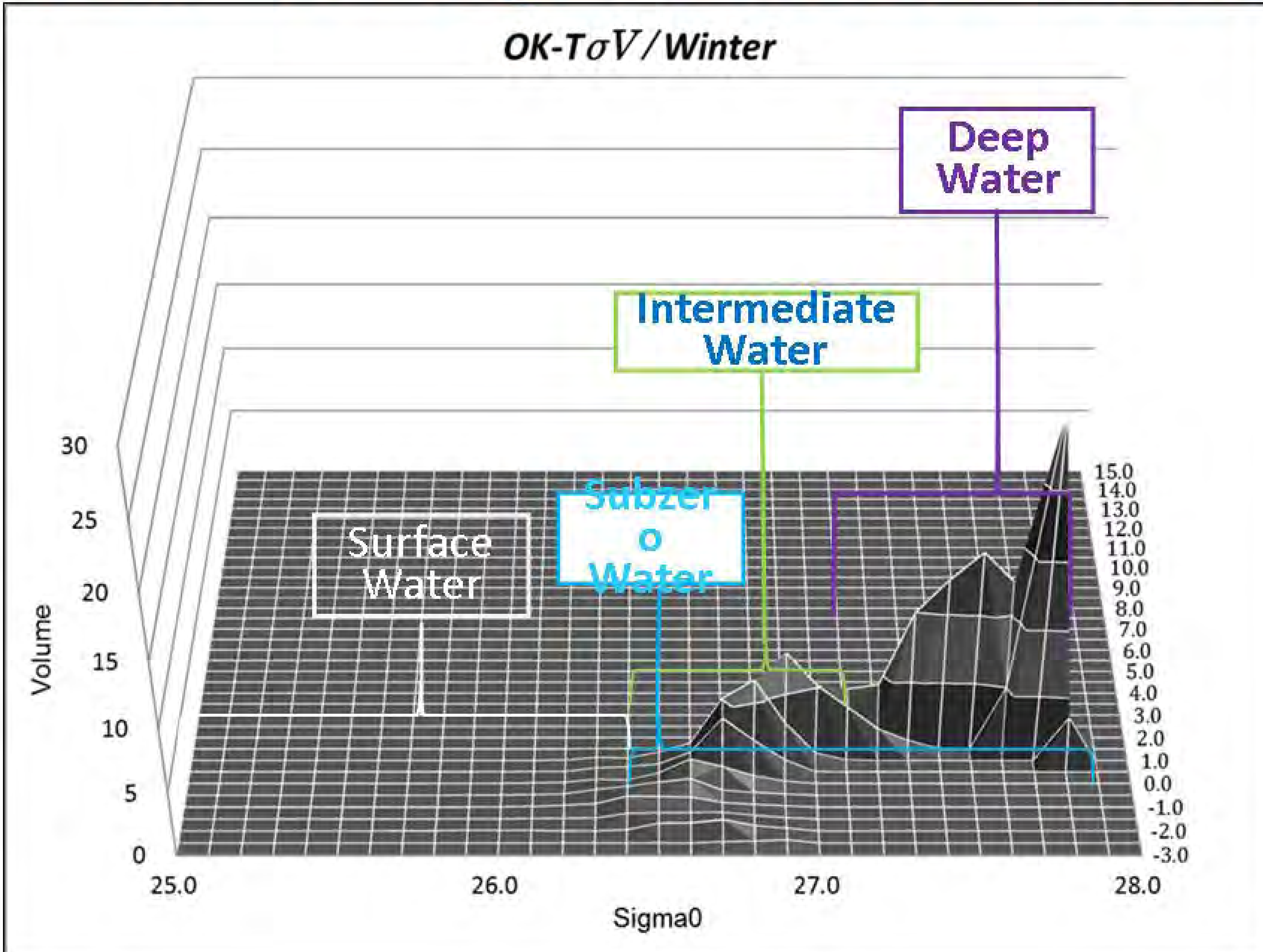
  1. Analyzed Data: WOA09 $1^{\circ} \times 1^{\circ}$ mesh monthly standard depth data of182 stns in the Sea of Okhotsk ;
  2. Digitized: $\Delta D = 10$ m; $\Delta Tpt_0 = 0.5\,^{\circ}C$; $\Delta \sigma_0 = 0.1\ kg{\cdot}m^{-3}$; $\Delta S = 0.1$ psu;
  3. Calculated parameters: volume of element watermass, volume-weighted-mean Tpt_0 , σ_0 , S of element watermass;

Why, the Sea of Okhotsk?

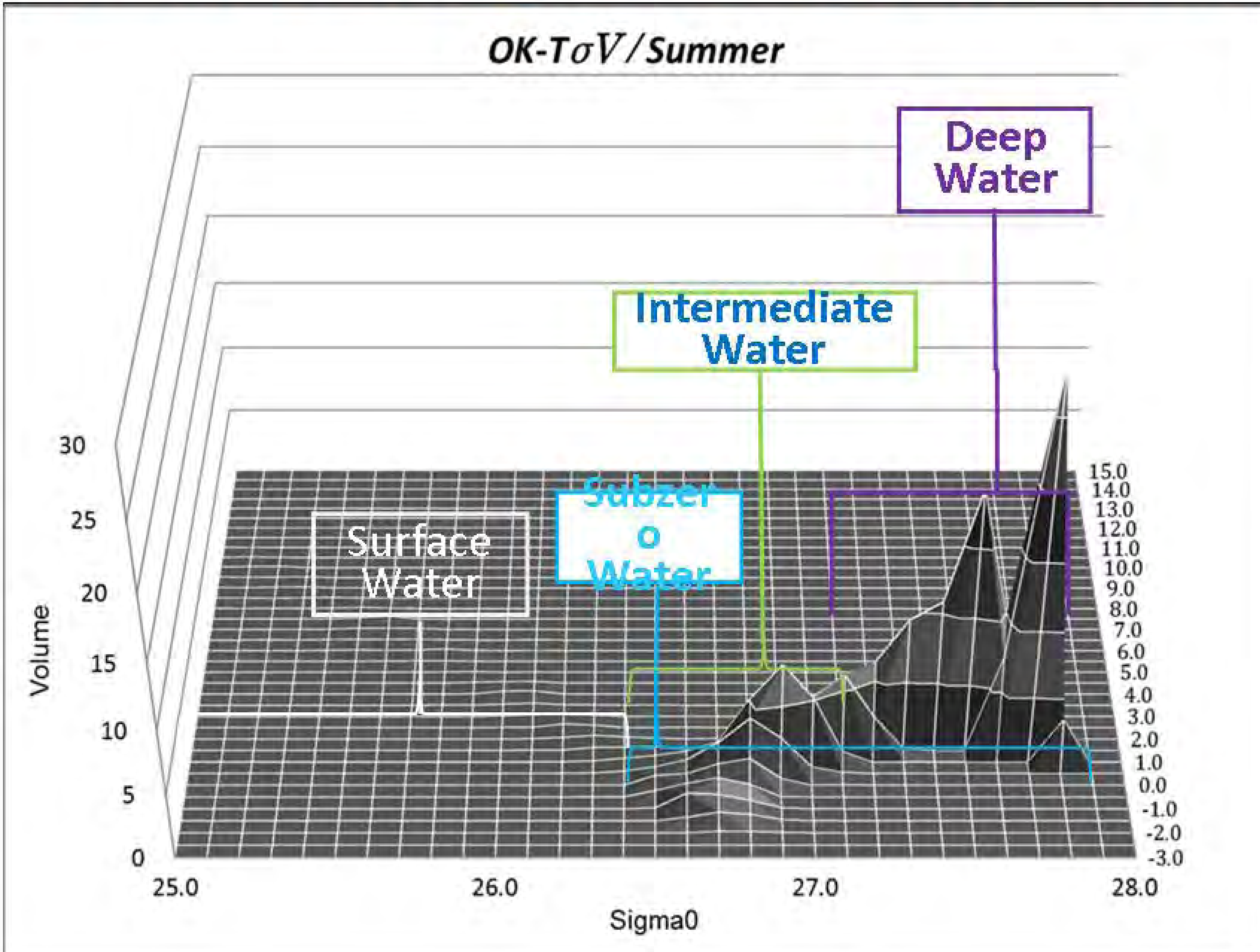


- ✓ **Black Contour & Color Pattern**: Winter Tpt on Sigma=26.7 : representative density of NP Intermediate Water; by WOA09 data
- ✓ **White Contour**: Stream-line of Subarctic Gyre in Winter= Depth contour of Sigma=27.0 surface (= main pycnocline); byWOA09 data
- ☐ *Cooling of NPSAW occurs mainly in the Sea of Okhotsk;*

Winter TσV diagram of the Sea of Okhotsk



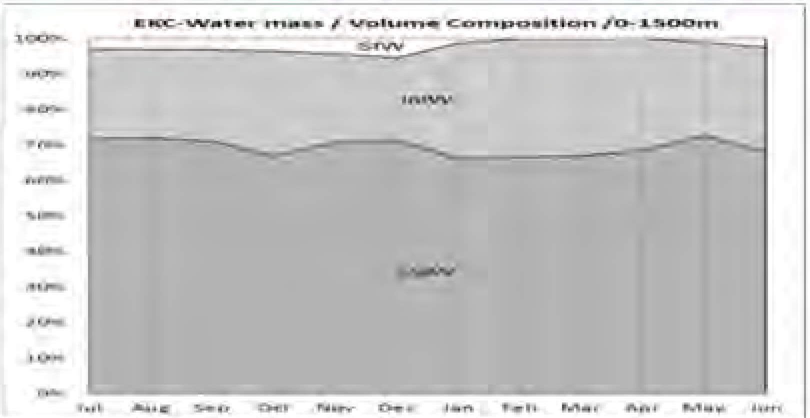
Summer TσV diagram of the Sea of Okhotsk

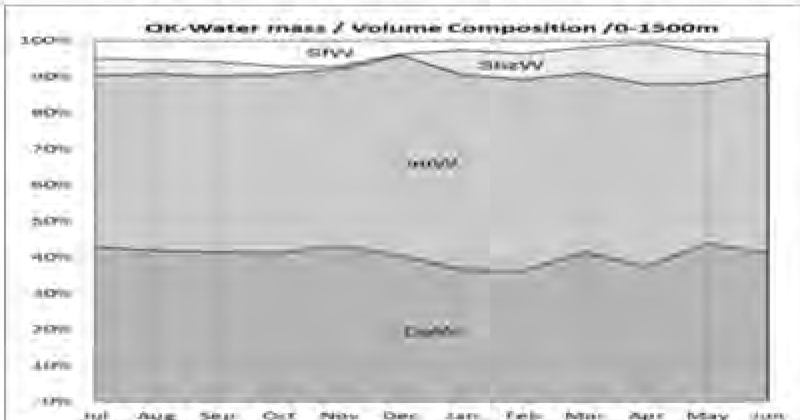


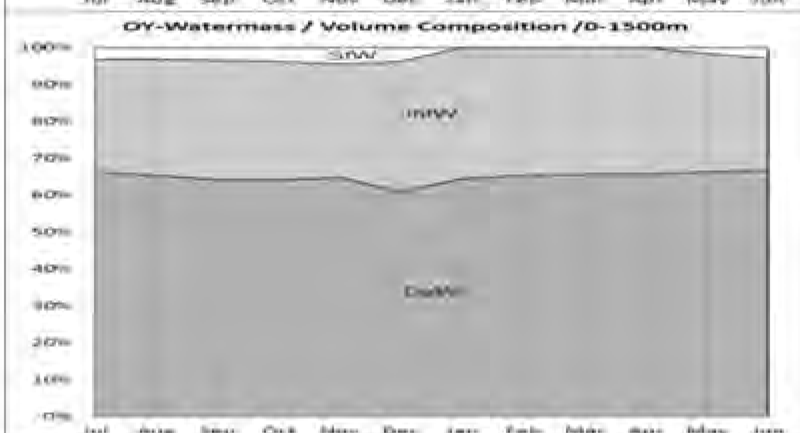
Boundaries of Identified Element Watermasses of the Sea of Okhotsk

Watermass	σ_0		Tpt		Physical Boundary	
	Btm	Top	Btm	Top	Btm	Top
SfW		<26.4			Bottom of Surface Stratification	Sea surface
SbzW	$26.4\leq$			<-0.5	(Sea floor)	Pycnocline
IntW	$26.4\leq$	<27.1	$-0.5\leq$		Pycnocline	Pycnocline
DpW	$27.1\leq$				Sea floor	Pycnocline

Events in seasonal cycle: *Volume of Element Watermasses*



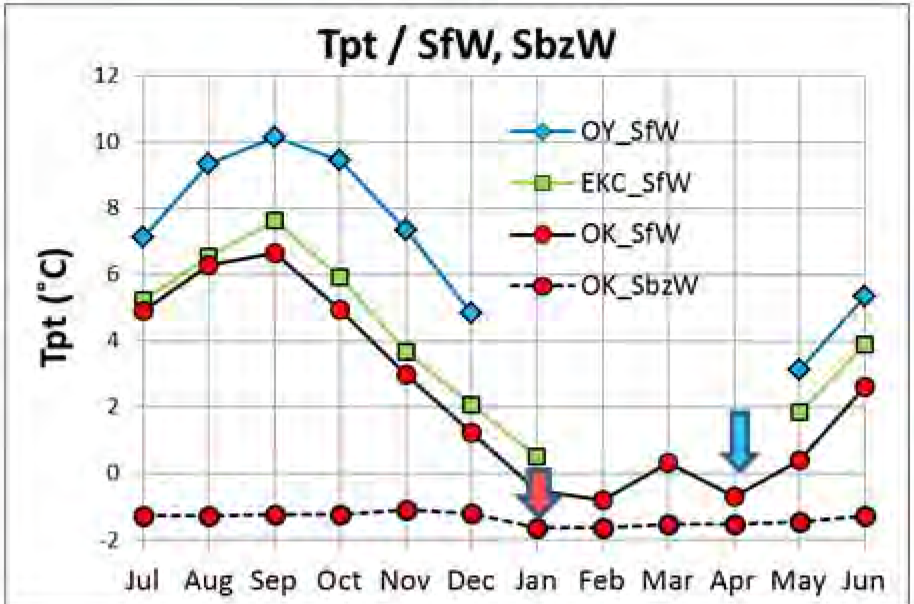


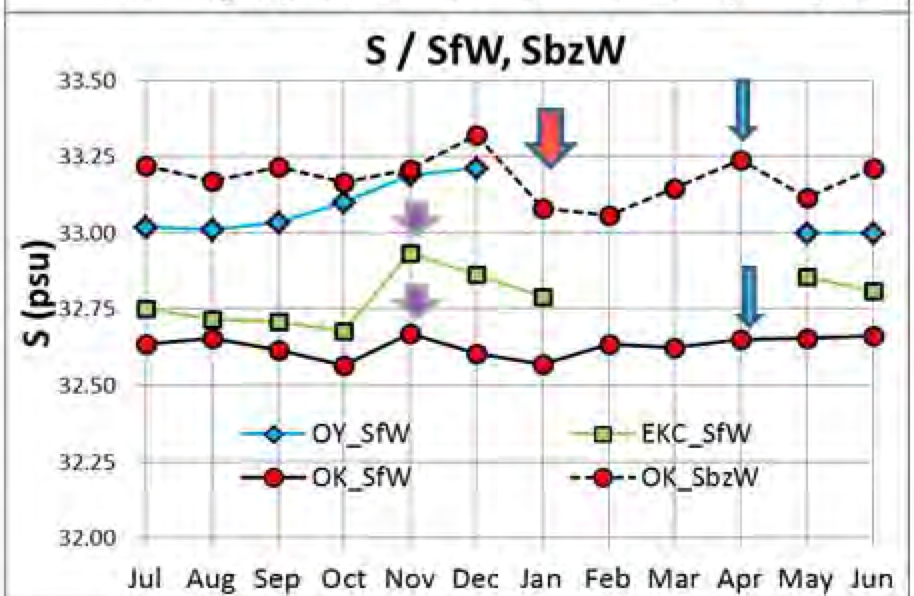


- ✓ **EKC Water**:
  - SfW disappear in Jan ~ Apr;
  - Boundary between IntW and DpW deepen in Oct and Jan ~ Apr;
  - No SbzW;
- ✓ **OK Water**:
  - SfW exist all through the year ;
  - SbzW start decrease in autumn and almost disappear in Nov and Dec, but almost recover in Jan;
  - Boundary between 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 seaice 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):

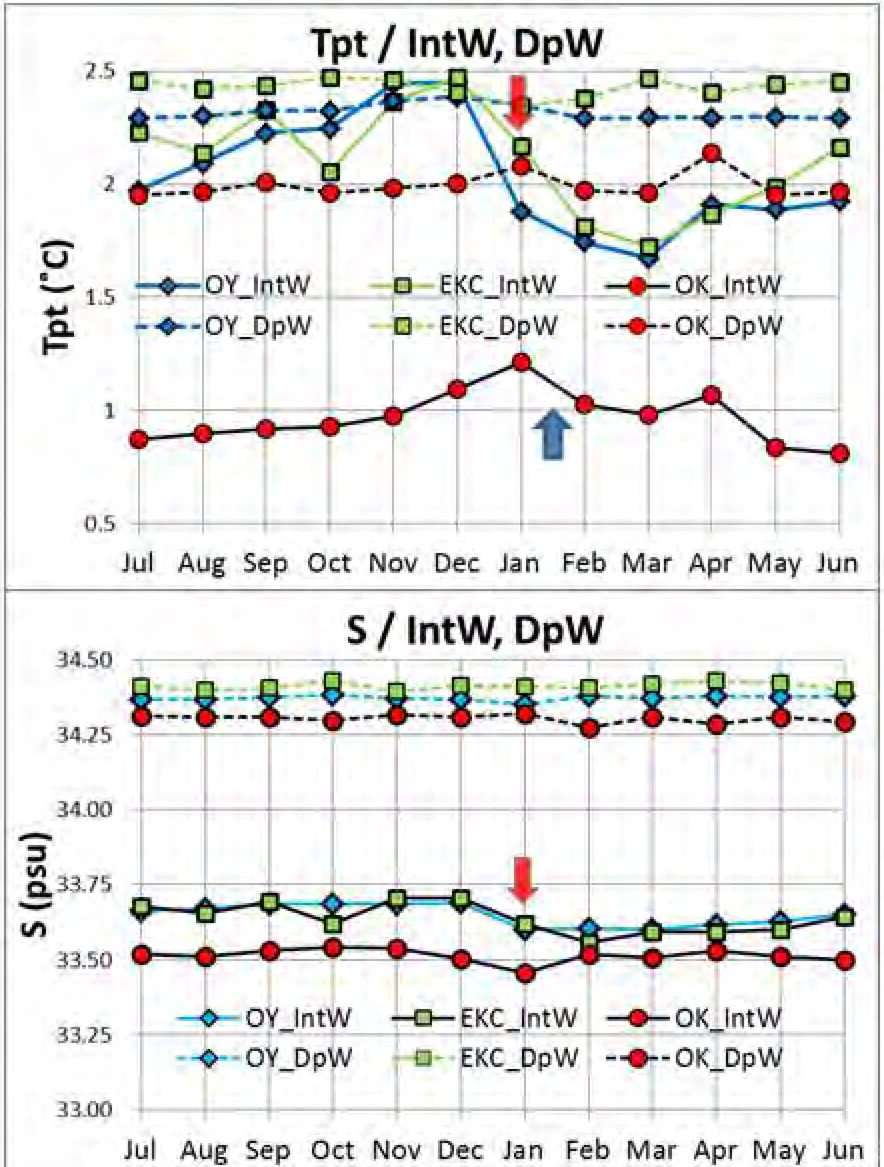
✓In **Jan**, T/S drop:

- Considering with volume recovery of in Jan, SbzW is produced in Jan;
- Salinity drop can be caused by concurrent freezing/melting at seaice development (Watanabe *et.al.*, 2004);

✓In **Apr**, salinity of SbzW shows temporal maximum, while temperature is almost unchanged;

- ☐ Why, salinity maximum at seaice 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*

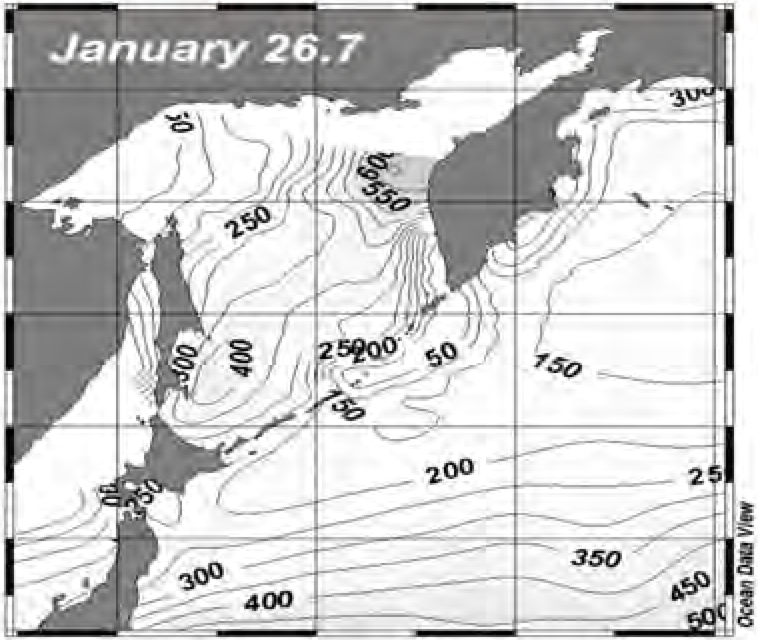
Number of stations where element watermasses are surfacing (WOA09 data, total stations in the Sea of Okhotsk=182).

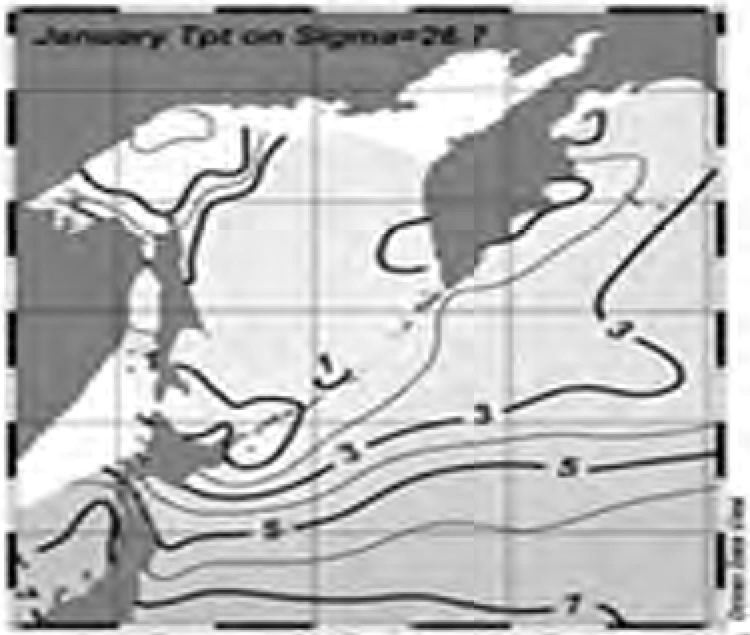
Month	SbzW	IntW
Oct	0	0
Nov	0	0
Dec	0	46
Jan	5	44
Feb	0	45
Mar	0	31
Apr	91	9
May	0	8
Jun	0	0

- ✓ 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?

January Event: ***Density surface $\sigma = 26.7$ topography and Tpt on it***

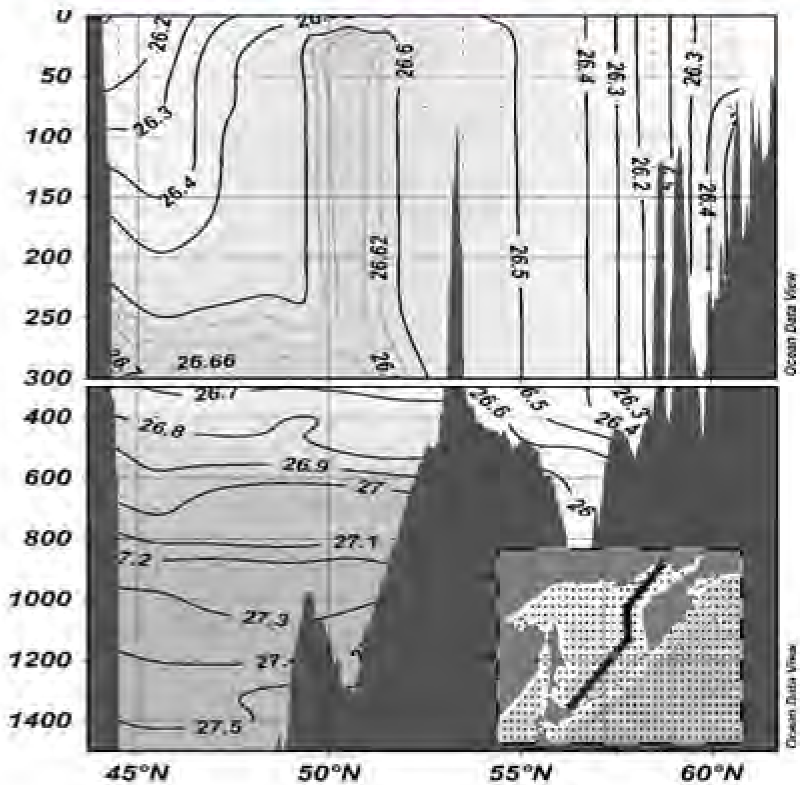


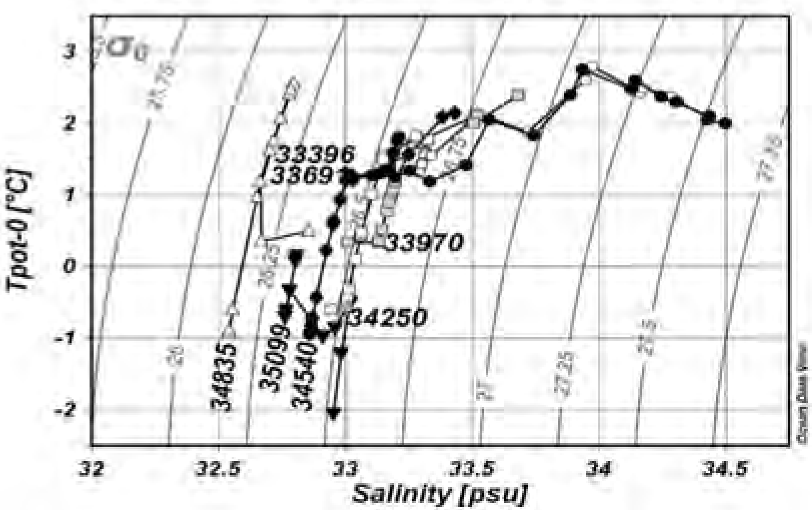


Density surface σ =26.7 : representative density of IntW;

- ✓**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 σ =26.7 surface**: *lower panel*
  - The water of Tpt ≤0°C, *i.e.* SbzW, distribute only in the NW Shelf Region, where is under ice cover;

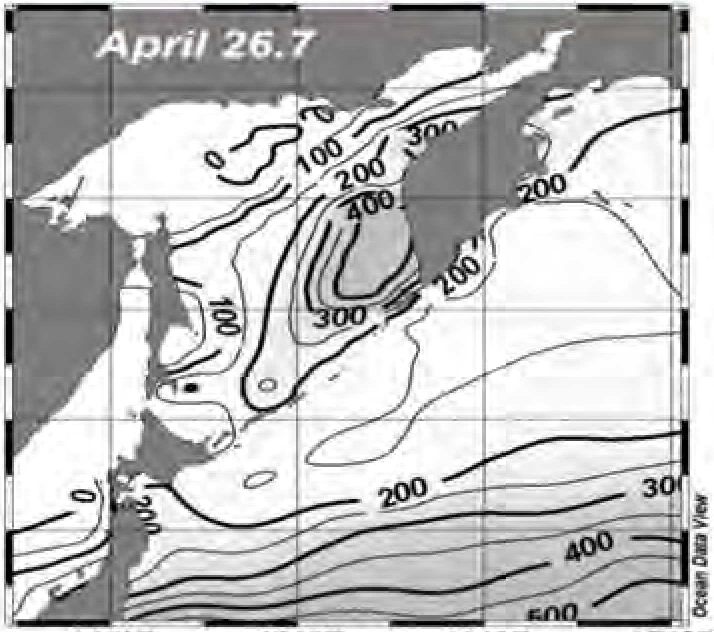
January Event: NE-SW density section and T/S diagram

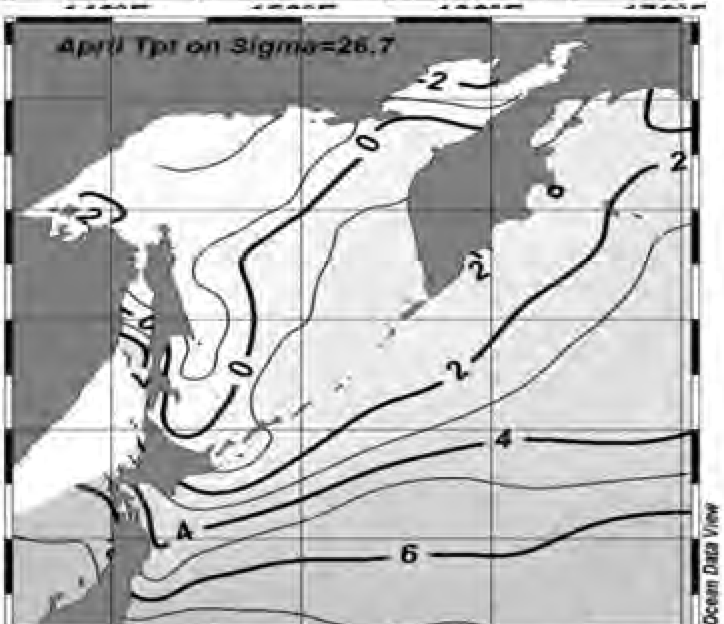




- ✓ **NE-SW density section** (upper panel):
  - **NE part**(right-hand side): The density contours of σ = 26.2 ~ 26.5 show broad depression, indicating clockwise local gyre. In this gyre, the isopycnals forming this depression are standing vertical (i.e. pycnostad) ;
  - **North Kuril Islands section** (central part): The isopycnal of σ = 26.60 ~ 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 ≤ 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

Preconditioning & Driving factors	Region of Winter Deep Convection			
	Gulf of Lion	Labrador Sea	Norwegian Sea	Sea of Okhotsk
Pycnostad	○	○	○	○
Circulation	Cyclonic	Cyclonic	Cyclonic	Cyclonic + Anti-cyclonic
Strong wind	○	○	○	○
Strong cooling	○	○	○	○
Open water	No Seaice	○	○	○
Salinity supply	Mediterranean Intermediate Water	North Atlantic Subarctic Water	North Atlantic Subarctic Water + Seaice formation	Seaice formation
Outcrop water	West Mediterranean Deep Water	Labrador Water	Greenland Sea Water	Okhotsk Sea Intermediate Water

(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 occures in **Dec~ Apr**, which is the response of the main pycnocline of Subarctic NP to spin-up of Subarctic Gyre;