Mechanism of warming the Okhotsk Sea Intermediate Water, from consideration on seasonal cycle

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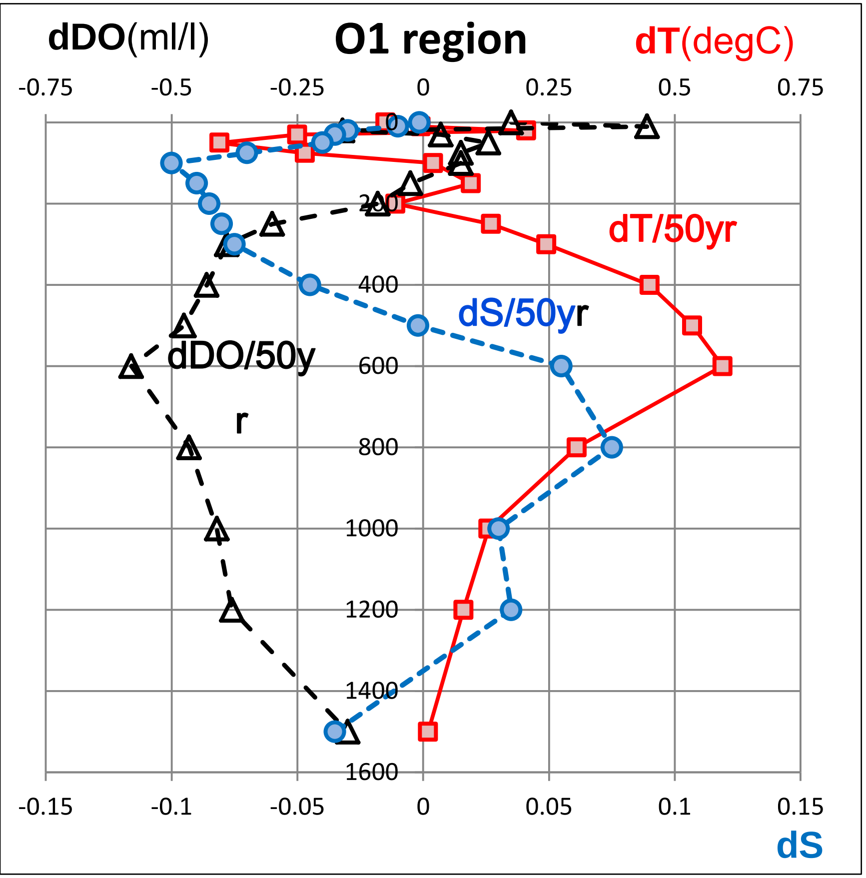
1. Introduction: 1-1. Facts and explanation failed

- ☐ **Fact**: (Nakanowatari *et al*., 2007)
  - ✓ *Warming and DO-decreasing 50yr trend at the intermediate isopycnal surfaces exists in the Okhotsk Sea and spread toward Subarctic Pacific.*
- ☐ **Tentative explanation:**
  - ✓ *Effect of atmospheric warming from surface via DSW to OKIW.*
  - ∵ Decreased DSW production →weakening of cooling IntW→ Warming;
  - ∵ Increased surface stratification → weakening DO supply → DO decrease;
- ☐ **Facts against this explanation**:
- ■ DO decrease by increased surface stratification is the only event of warm season for the Okhotsk Sea. In winter, at the open Subarctic Pacific and the open sea-ice area of the Okhotsk Sea, the surface thermocline disappears during winter!!
- ■ Warming beyond $27.1\sigma_0$ is deeper than the limit of ventilation by DSW in the Sea of Okhotsk, shown by CFCs distribution (Wong *et al*., 1998)!!
- ■ Cannot explain associated S increase necessary as facts on isopycnals!!
- ■ OKIW can mix with the subsurface temperature max layer and the DO min layer, during all seasons!!

1-2. Revisit the evidence to see all the aspects



Depth and Depth-interval changes of isopycnals 1976/2026,

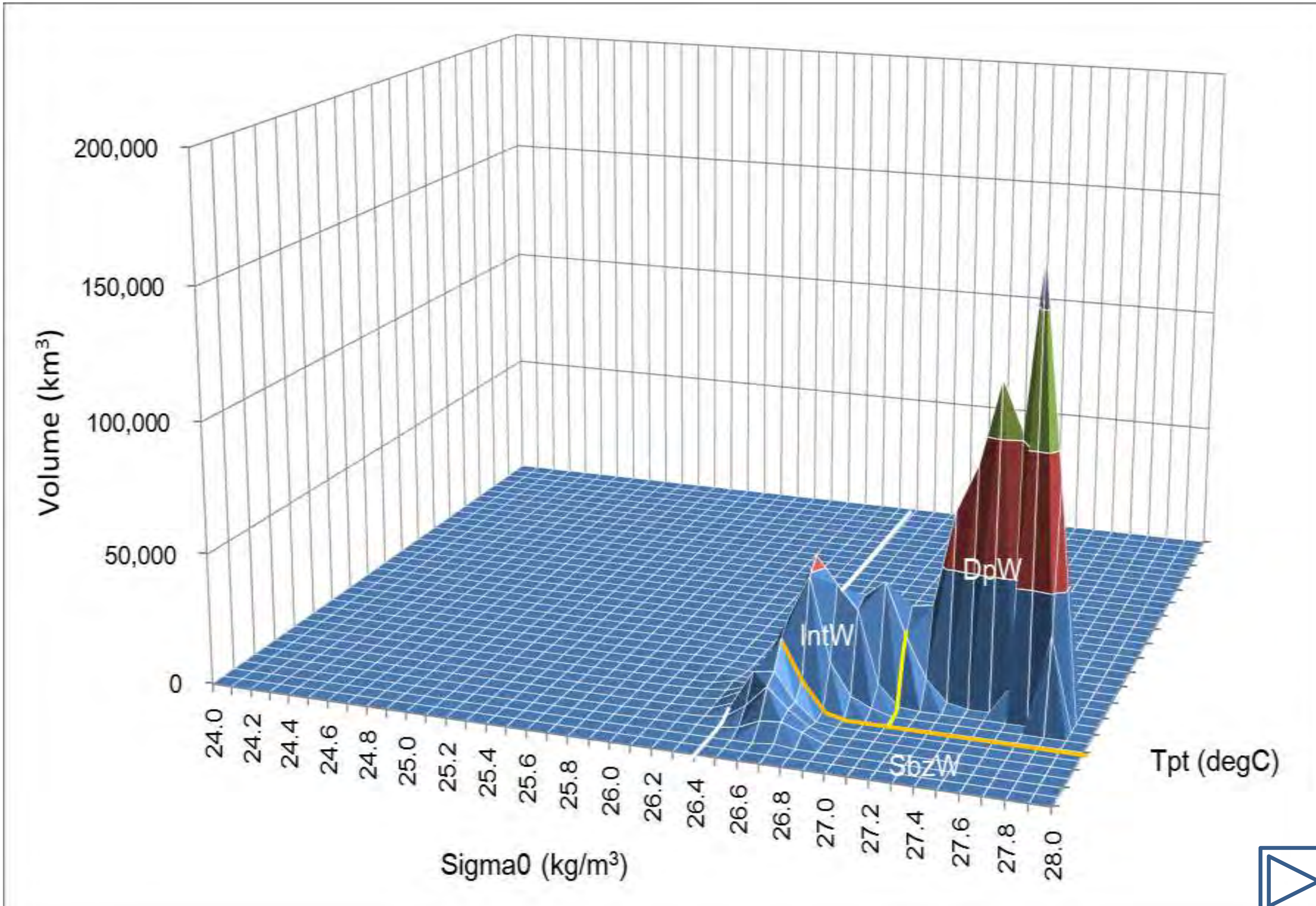
Isopycnals [kg/m^3]	Depth 1976	Depth 2026	$\Delta_t D$	$\Delta_d D$
26.4	61	66	**+5**	
				+20
26.5	75	100	**+25**	
				+20
26.6	120	165	**+45**	
				+26
26.7	179	250	**+71**	
				+42
26.8	250	363	**+113**	
				-60
26.9	400	453	**+53**	
				-22
27.0	500	531	**+31**	
				-31
27.1	600	600	**0**	
				-73
27.2	800	727	**−73**	
				+37
27.3	891	855	**−36**	
				+36
27.4	1000	1000	**0**	

- **Data:** Climatic Atlas of the North Pacific Seas 2009 , The Sea of Okhotsk, NOAA
- **T, S, DO and Depth anomalies** in the sub-region O-1 after 50yrs :
- **Deepening** isopycnals above 27.1 σ_0 ; **stable** 27.1 σ_0 at 600m**; shallowing** below
  = Sharpening of pycnocline at 27.1σ_0:
  - Deeper potential vorticity maximum layer = pycnocline (**Freeland *et* al., 1998**);
  - Lower boundary of atmospheric ventilation shown by CFCs (**Wong *et al.*, 1998**);

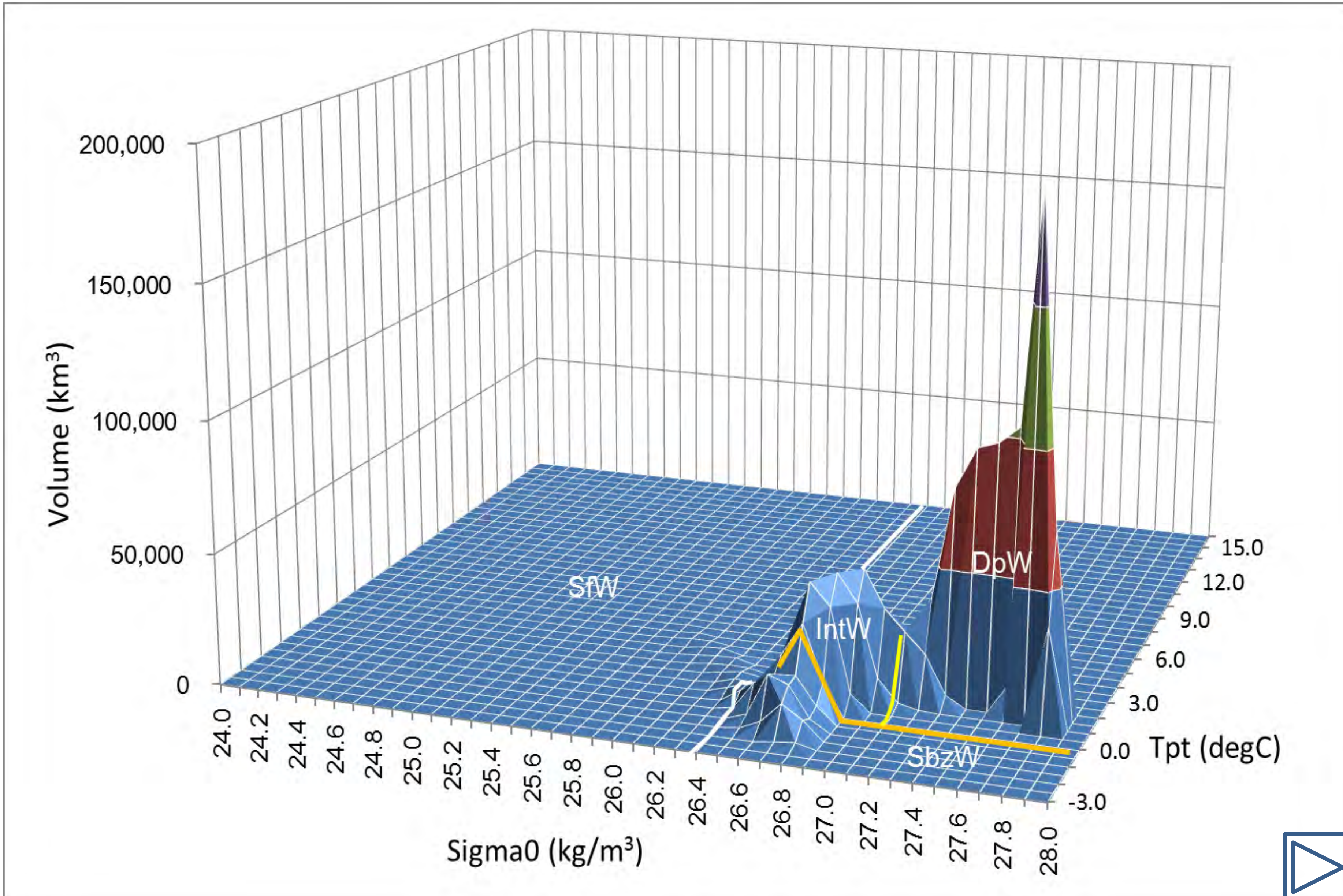
2. Scientific Question

- *Question*: *What causes T/S/D increase and DO decrease at intermediate isopycnal surfaces??*
  - ✓ **Explanatio**n must be clear on the watermass processes in terms of:
    - *Seasonal cycle* of OKIW = Seasonal cycle is the largest forcing on the planet of Earth;
    - *Cause-and-effect relation* = interactions between water elements as substantial objects = This is 'explanation' in physics.
  - ✓ **Deduced Question**:
    - How to identify *water elements as substantial objects* , whose state-variables can be measured and described by mass-balance-rule?
      - TσV-diagram
    - How to identify forcing factors causing changes in IntW properties?
      - 3D-T/S/DO-climograph;
      - 3D-ΔT/S/DO-diagram

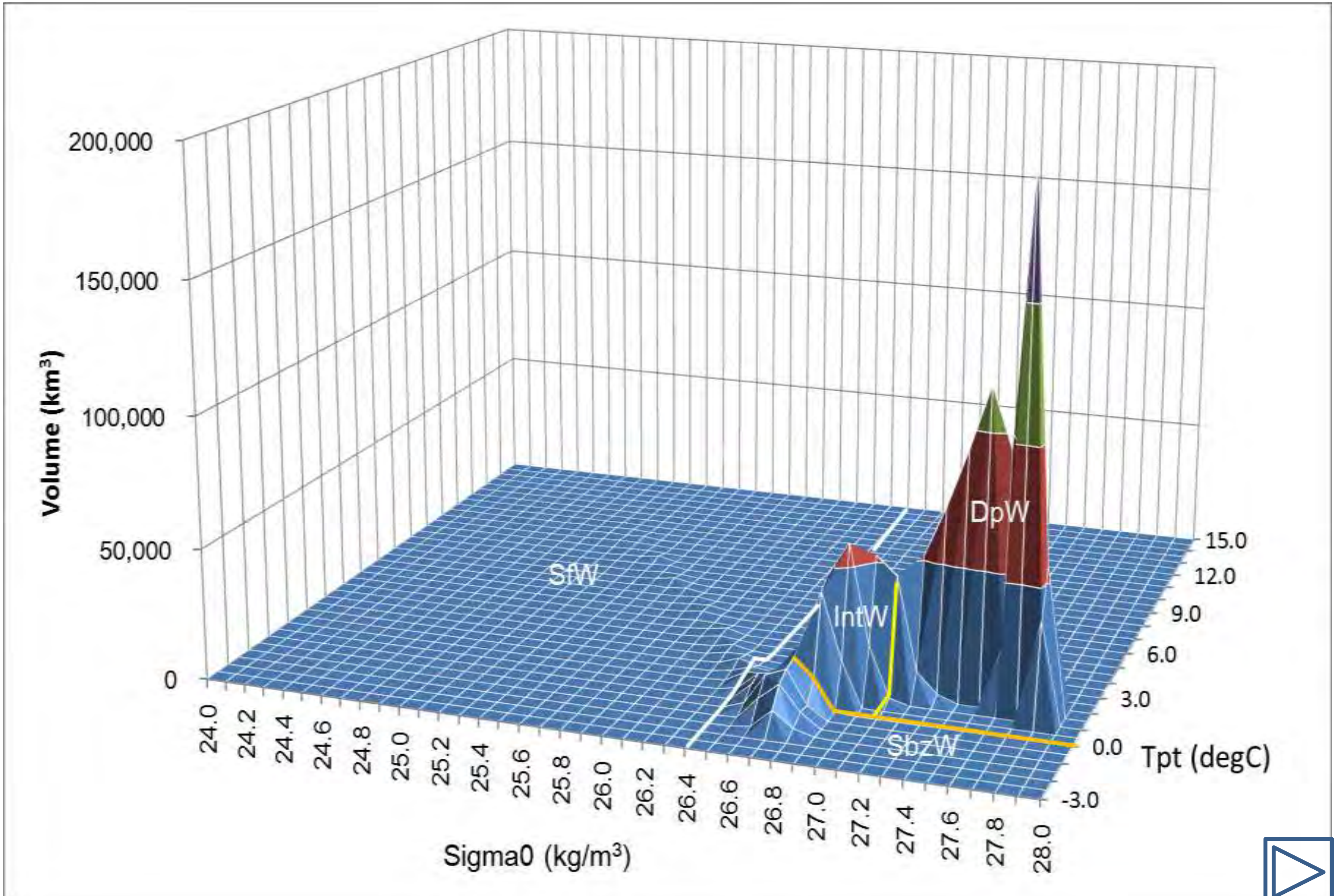
2-1a. TσV-analysis: Winter



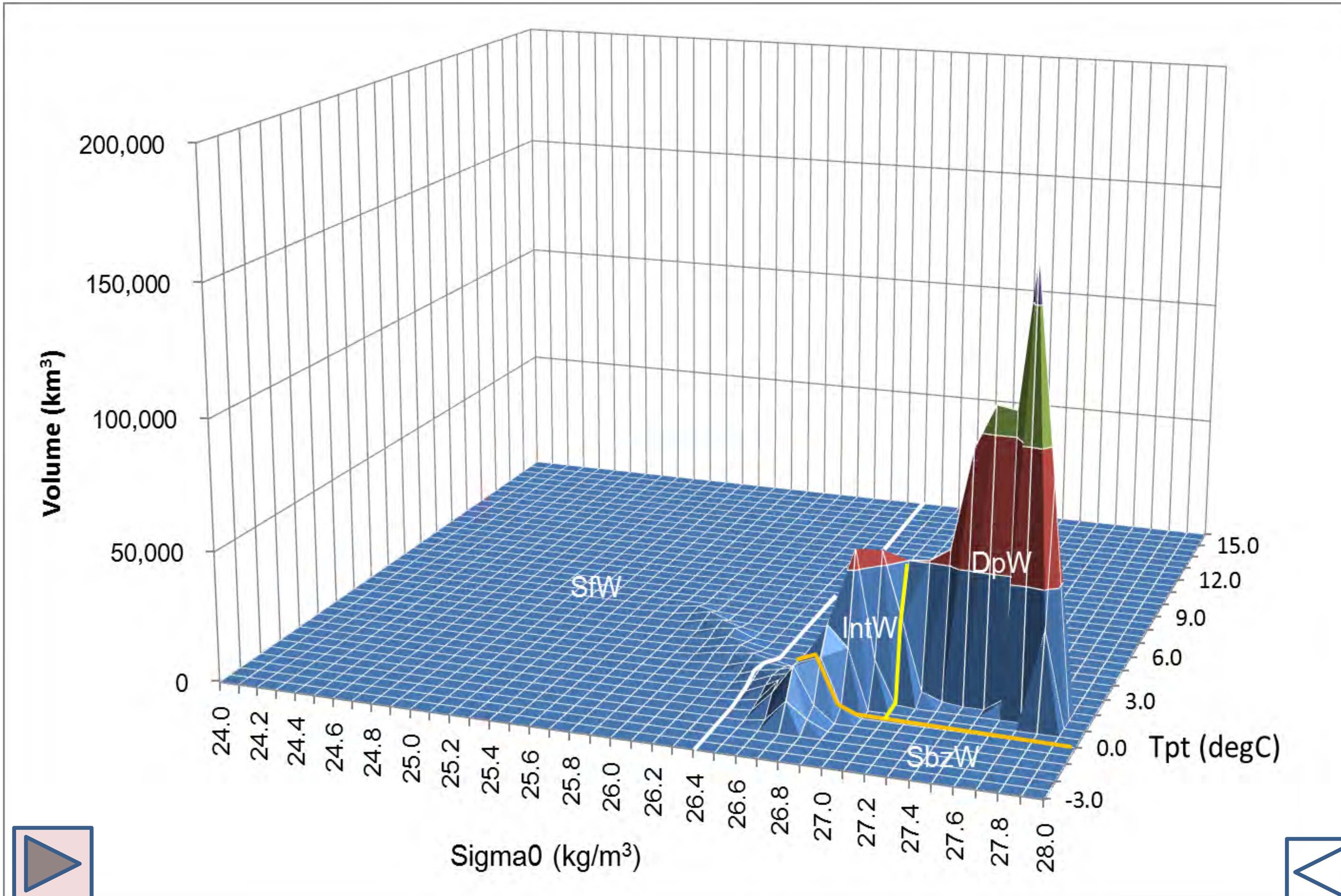
2-1b. TσV-analysis: Spring



2-1c. TσV-analysis :Summer



2-1d. TσV-analysis Autumn



2-2. Element Waters Identified by TσV-diagram

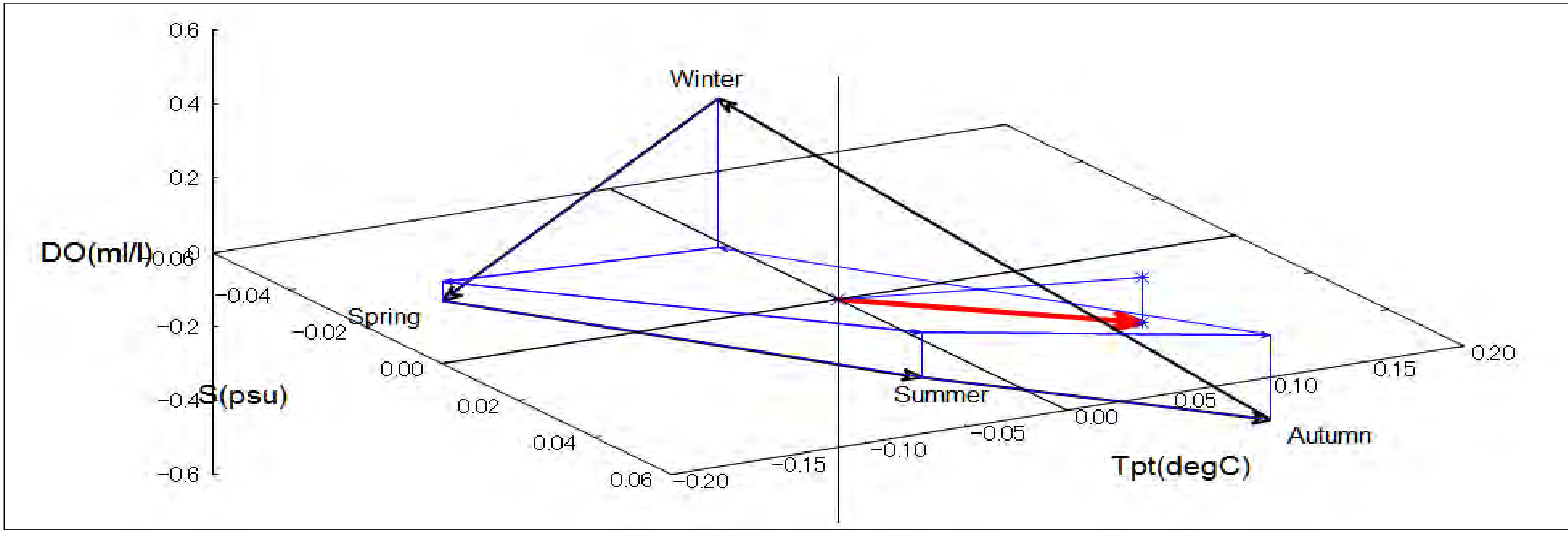
- The components of the Okhotsk Sea water are identified as heaps of mountains or plateaus in TσV-diagram, as bounded by **stable** valleys or cliffs (*i.e.* pycno/thermocline or front) and named as *Element Waters* of the Okhotsk Water.
- Following four element waters are identified as the components of Okhotsk Water:

Element Water	**Symbol**	**σ_0 Range** (kg/m^3)	**T_{pt} Range** (degC)
Surface Water	SfW	< 26.4	
Subzero Water	SbzW	26.4 ≤	≤ 0
Intermediate Water	IntW	26.4 – 27.0	
Deep Water	DpW	27.1 ≤	

- IntW and DpW show *significant seasonal changes*.
- The *isopycnal surface* ***27.1 σ_0*** appears as the boundary between IntW and DpW.

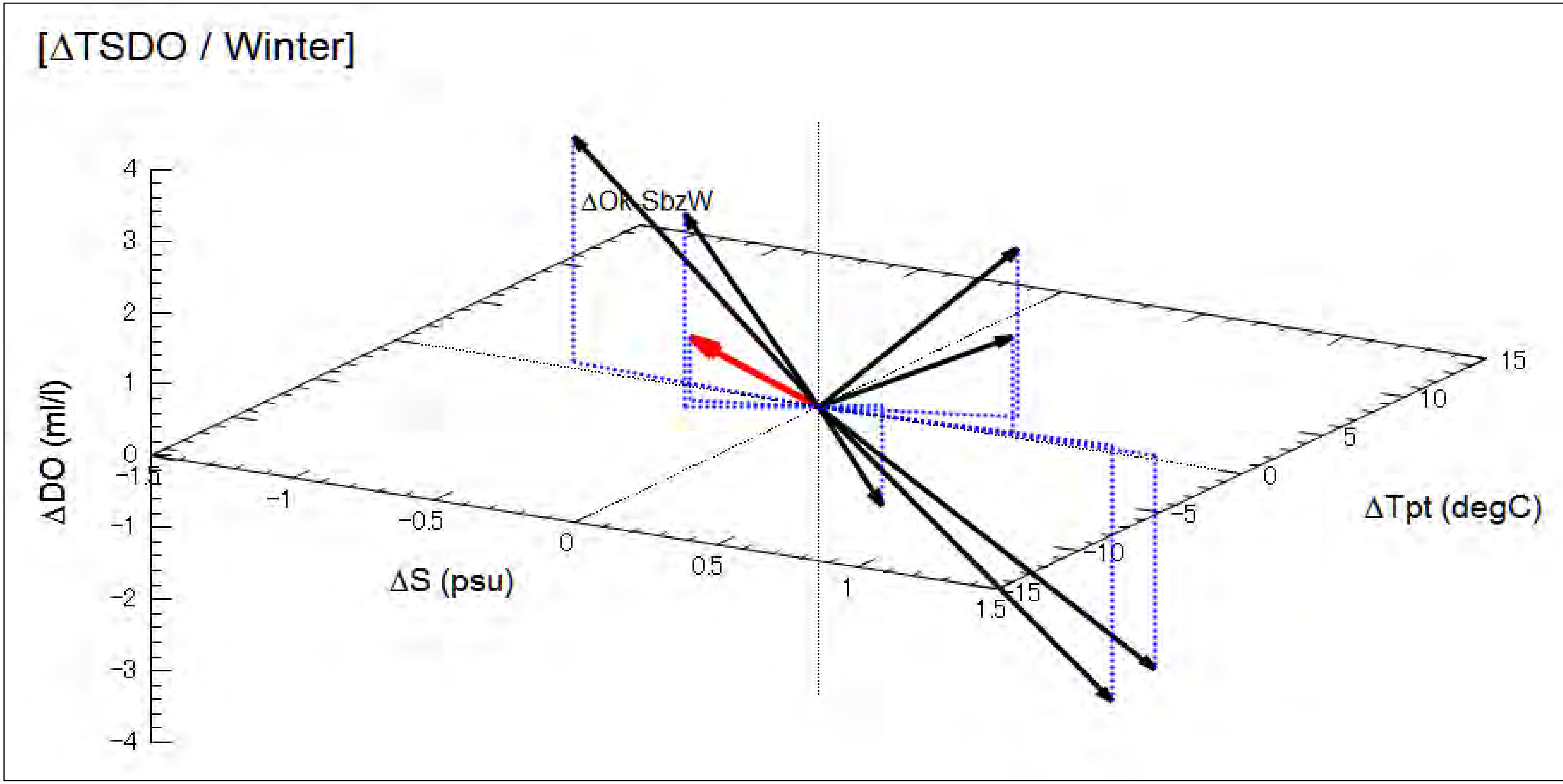
- For the each element water, the average Tpt, S, and DO were calculated as volume-weighted-mean.

3. Seasonal Cycle of IntW: 3-1. 3D-Climograph



- **3D-Climograph**: a diagram connecting seasonal anomalies from annual mean, and displacement by trend anomaly for 10yrs, on Tpt/S/DO-coordinate;
  - Winter: T ≈ 0 ; S ≈ **Min** ; DO = **Max**;
    FW/DO input by mixing w/ SfW ?:
  - Spring : T = **Min** ; S = **Min** ; DO ≈ 0 **--**;
    falling down of spring bloom ?:
  - Summer: T ≈ 0 **++**; S = **++**; DO = **-**;
    T/S/DO input by mixing w/ ???:
  - Autumn: T= **Max --**; S = **Max** ; DO **=** **Min**;
    Cooling by ventilation ???

3-2. ΔT/S/DO-diagram
a. Winter



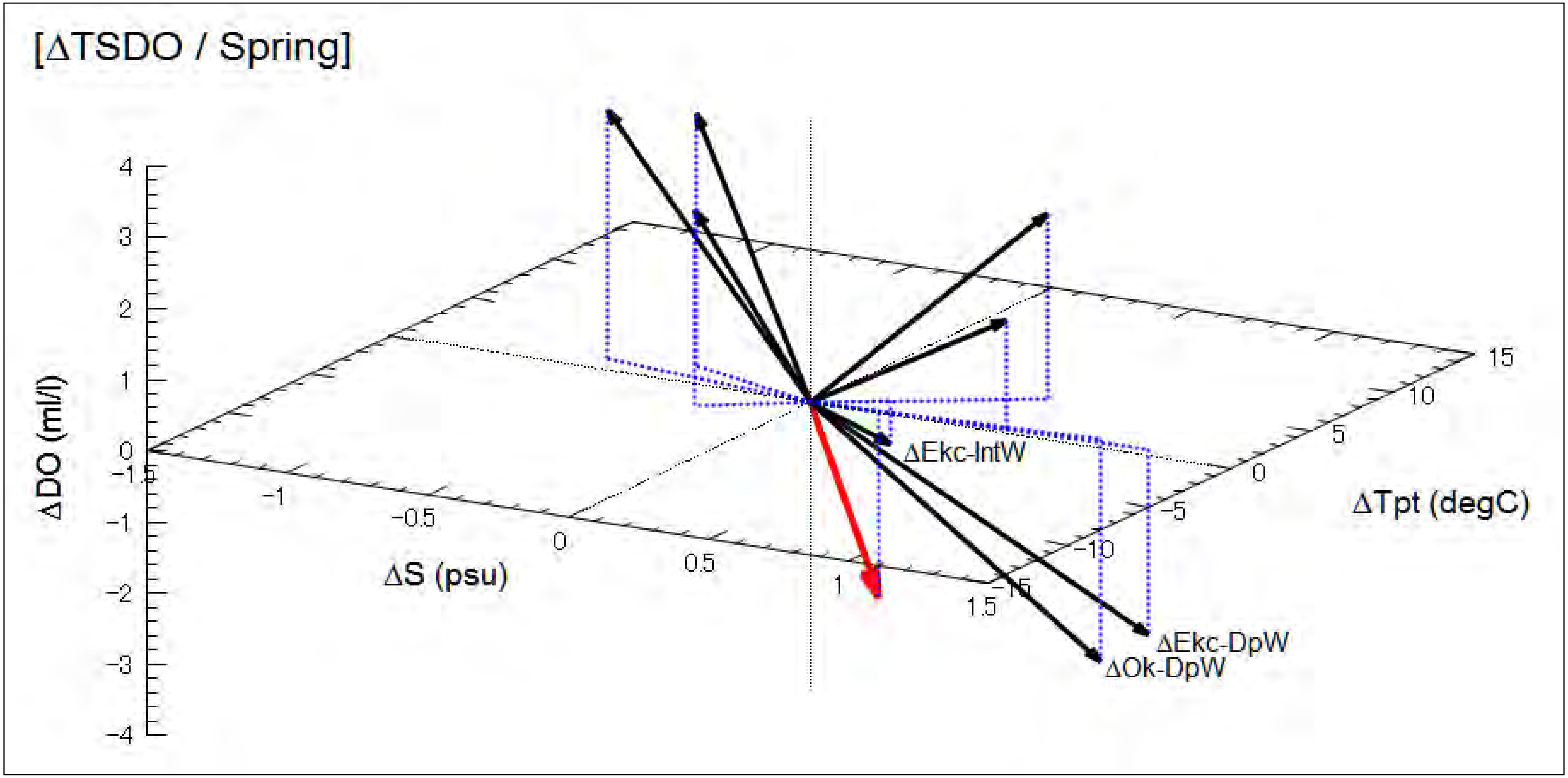
→ **:** Mean time-change rate of Tpt/S/DO of IntW at winter,

ΔTpt/ΔS/ΔDO: Difference between Tpt/S/DO of IntW and other element waters possible to mix with,

Forcing Vector in the same direction:

ΔOk-SbzW

3-2. ΔT/S/DO-diagram
b. Spring



→ **: Mean time-change rate at spring**

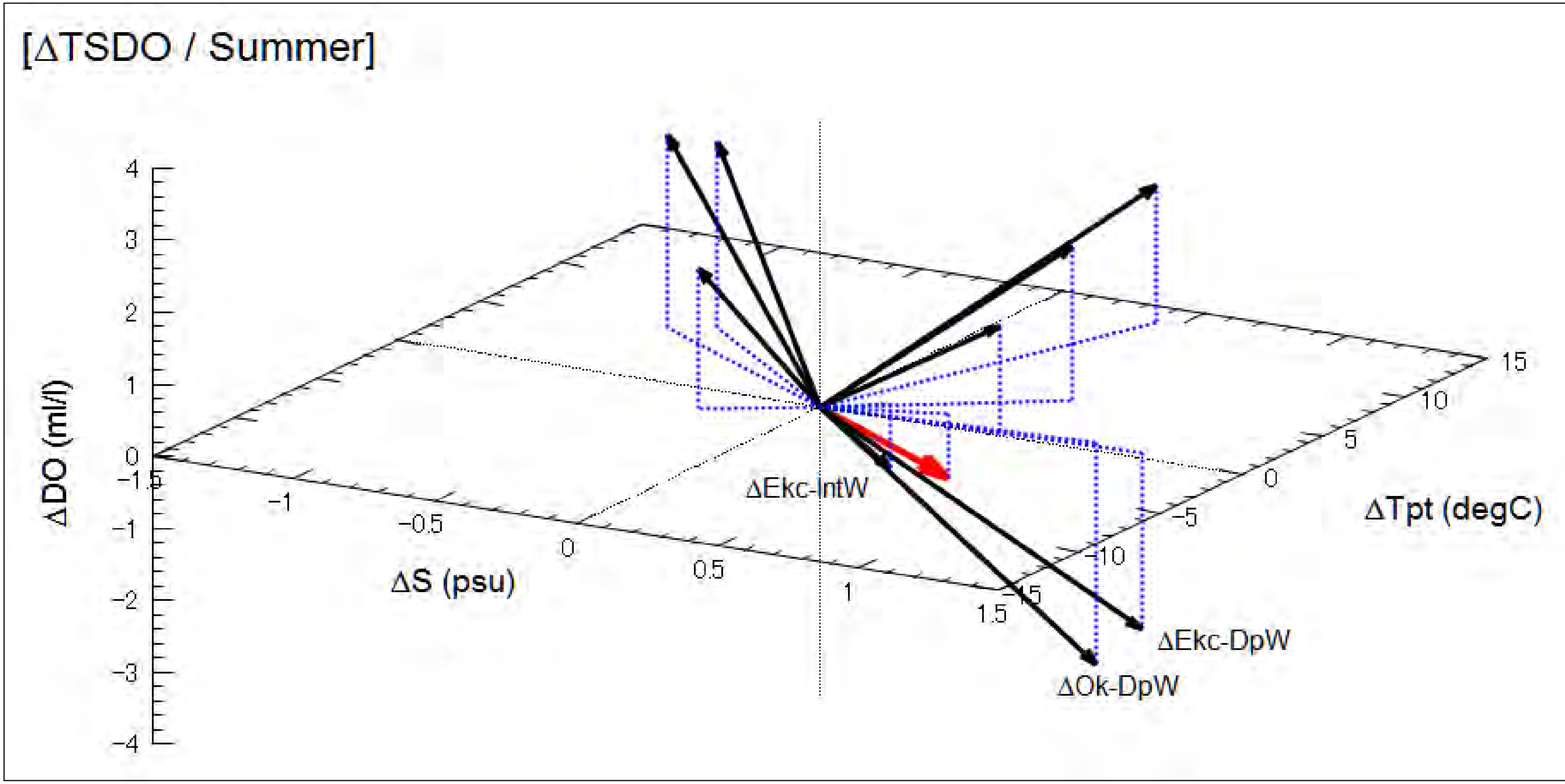
Forcing Vector in the same direction:

ΔOk-DpW

ΔEkc-DpW

ΔEkc-IntW

3-2. ΔT/S/DO-diagram-
c. Summer



→ **: Mean time-change rate at summer**

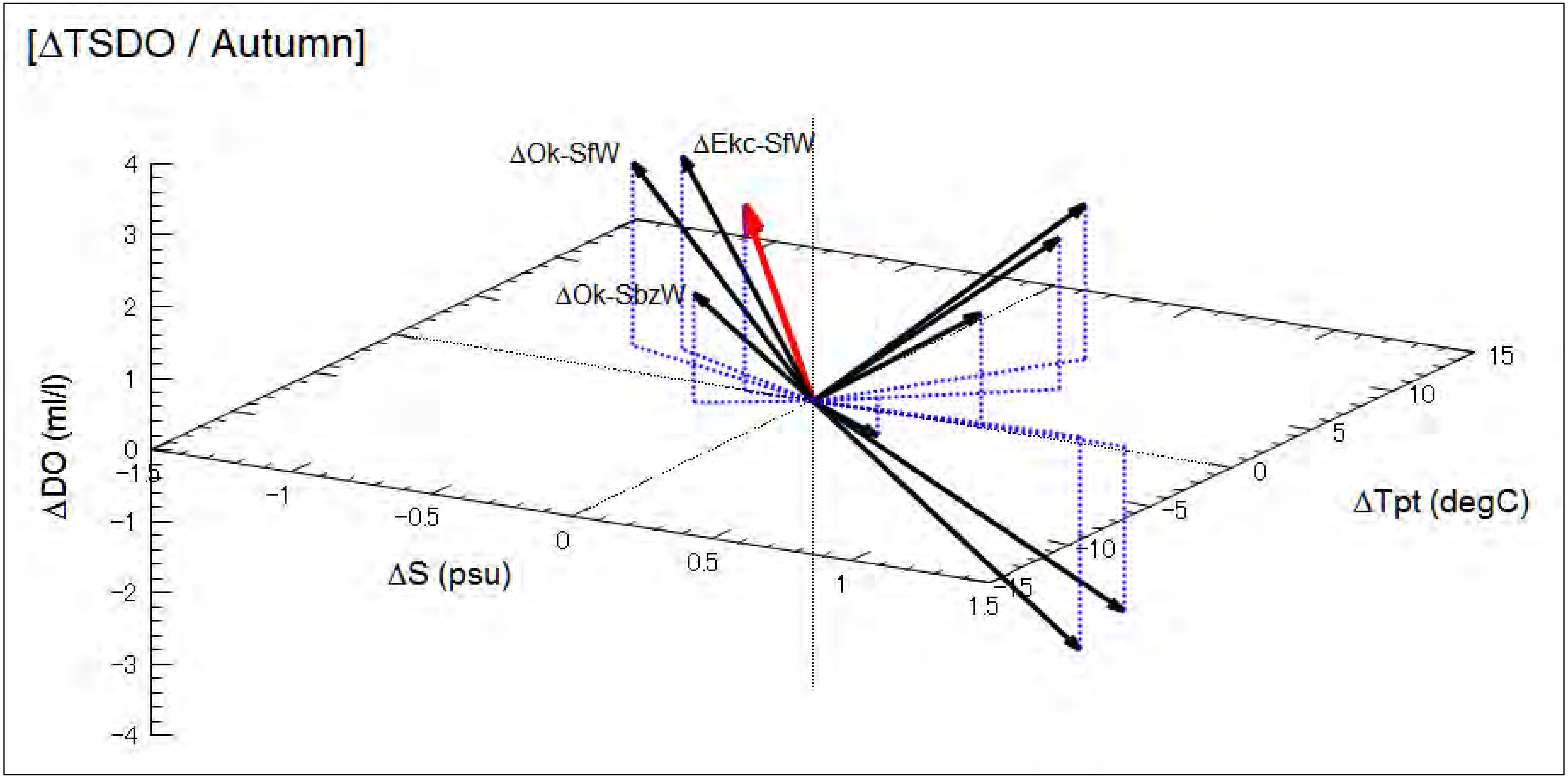
Forcing Vector in the same direction:

ΔOk-DpW

ΔEkc-DpW

ΔEkc-IntW

3-2. ΔT/S/DO-diagram-
d. Autumn



→ **: Mean time-change rate at autumn**

Forcing Vector in the same direction:

ΔOk-SbzW

+ ΔOk-SfW

+ ΔEkc-SfW

3-4. Identified forcing factors

- The forcing factors can be divided into 3 categories:
  - **Primary Factor**(s), of which increase makes time-change of IntW,
  - **Reverse Factor**(s), of which decrease makes time-change of IntW,
  - Subsidiary Factor(s), of which changes do not affect straight to IntW.

Identified Primary/Reverse Forcing Factors by ΔTSDO-diagram

Season	IntW Change			**Primary Factor**	**Reverse Factor**
	Tpt	S	DO		
Winter	−	−	+	**Ok-SbzW**, Q/F*	Ekc-IntW, Ekc-DpW, Ok-DpW
Spring/ Summer	▪	+	−	**Ekc-DpW**, **Ok-DpW**, **Ekc-IntW**	Ok-SbzW
Autumn	▪	−	+	Ok-SfW, Ok-SbzW, Ekc-SfW	Ekc-IntW, Ekc-DpW, Ok-DpW

*During Dec - Mar, Ok-IntW surfaces at the open-ice stations.

- ***DpW*** contributes to ***S increase*** in *spring*/*summer!*

4 Consideration on long-term warming:
4-1. Seasonal cycle to Climate Change

- Volume of IntW indicates seasonal changes alternating between DpW: no show for economy of time
  - ✓ Seasonal change in depth of the boundary between (IntW/DpW) :
    - → Response of isopycnal surface to spin-up/down of WSAG;
      - → Response to seasonal change in strength of Siberian Monsoon;
- Enhanced atmospheric circulation can enhance the trend today:
  - Winter monsoon → Spin-up/down of WSAG;
  - Along-shore wind → Coastal upwelling;
  - Westerly wind → enhanced upper-layer effluent and lower-layer influent
    → enhanced contribution of DpW to IntW.

4-2. Up/downwelling of DpW and meridional circulation of the NW-Pacific Subarea #123

<table>
<tr><th>Boundary
σ_0 (kg•m^{-3})</th><th>Up/Down Welling
at the boundary</th><th>Watermasses
in the Pacific*</th><th colspan="2">Element Water in
the Okhotsk Sea</th></tr>
<tr><td>24.781</td><td></td><td rowspan="2">N-Pac_CtrW</td><td colspan="2" rowspan="3">Ok_SfW</td></tr>
<tr><td>25.561</td><td>Down Welling</td></tr>
<tr><td>26.131</td><td>Down Welling</td><td rowspan="4">N-Pac_IntW</td></tr>
<tr><td>26.495</td><td></td><td rowspan="3">IntW</td><td rowspan="3">SbzW</td></tr>
<tr><td>26.755</td><td>Down Welling</td></tr>
<tr><td>26.935</td><td>Down Welling</td></tr>
<tr><td>27.219</td><td>Down Welling</td><td rowspan="2">AA_IntW</td><td rowspan="3">DpW</td><td rowspan="5"></td></tr>
<tr><td>27.407</td><td>Down Welling</td></tr>
<tr><td>27.583</td><td>Up Welling</td><td>N-Pac_DpW</td></tr>
<tr><td>27.739</td><td>Up Welling</td><td>Upr-CrAA_DpW</td><td rowspan="2"></td></tr>
<tr><td>27.802</td><td>Up Welling</td><td>Lwr-CrAA_DpW</td></tr>
</table>

*Modified incorporating Tomczak et al., 2005 (Composed from **Macdonald *et al.*, 2009**)

- ✓ Pacific Ocean: DpW upwelling and downwelling is separated at $27.4\sigma_0$.
- ✓ Okhotsk Sea: the deepest layer is, in annual mean, at $27.69\ \sigma_0$.

☐ Coincidence with contribution of DpW in formation of OKIW!

5. Conclusions：

- Major forcing factor for the **seasonal cycle of Ok-IntW**:
  - Change in Ok-IntW at spring / summer: T+/S+/DO-:

    → caused by ***DpW*** *mixing into Ok-IntW*.

    coincides with 3D-circulation Pacific Ocean by Macdonald *et al*., 2009

    → result of *strong* ***vertical tidal mixing at the entrance***.
- Possible forcing factor for the **long-term trend** in Ok-IntW:
  - Amplified seasonal undulation of isopycnals at the effective sill depth of Kuril Strait:

    → results of NPSAG response to changes in atmospheric circulation .

6. Proposals:

- To understand seasonal dynamics, **PICES** should coordinate *Seasonal Observations on PICES Waters in WOCE-specifications*, for Next Generations: