Distribution and transport variations of source waters for North Pacific Intermediate Water formation revealed by multiple tracer analysis

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Background

*North Pacific Intermediate Water = NPIW

- NPIW is characterized by a salinity minimum layer in the subtropical gyre.
- The Mixed Water Region (MWR) is a formation site of NPIW (Talley 1993) .
- The ventilation source of NPIW is considered as the Okhotsk Sea (Yasuda 1997).
- However, the time variation of NPIW source waters are still unknown.

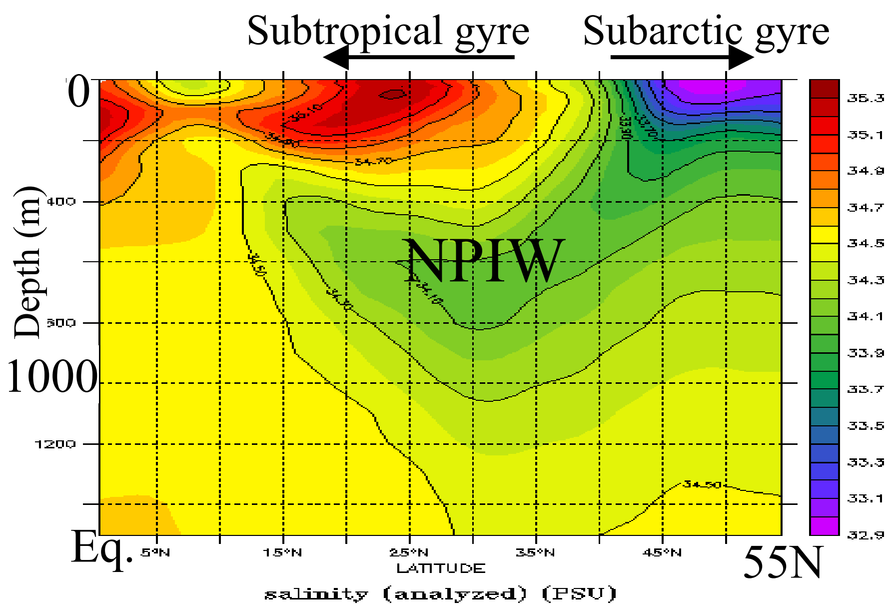


Fig. Vertical section of salinity along 170°E (World Ocean Atlas '98).

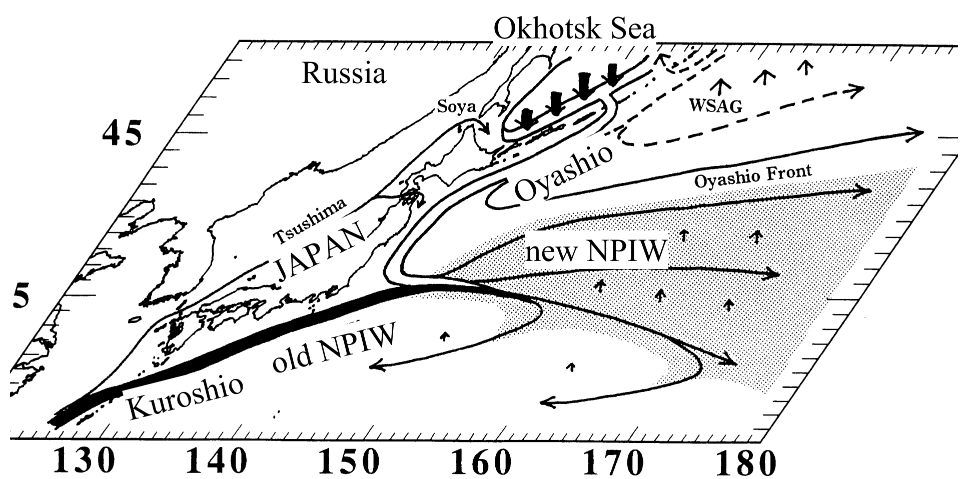


Fig. Schematic representation of NPIW formation (Yasuda 1997).

Our goal To reveal the time and spatial variation of NPIW source waters.

Methods

- Calculating the source water components (Kuroshio, Okhotsk Sea and East Kamchatka waters) in the mixed water by multiple tracer analysis.
- Examining the distribution of these source water components.
- Examining the time variation of the source water transports.
- The analyzed density range is from 26.7 σ_θ to 27.3 σ_θ .

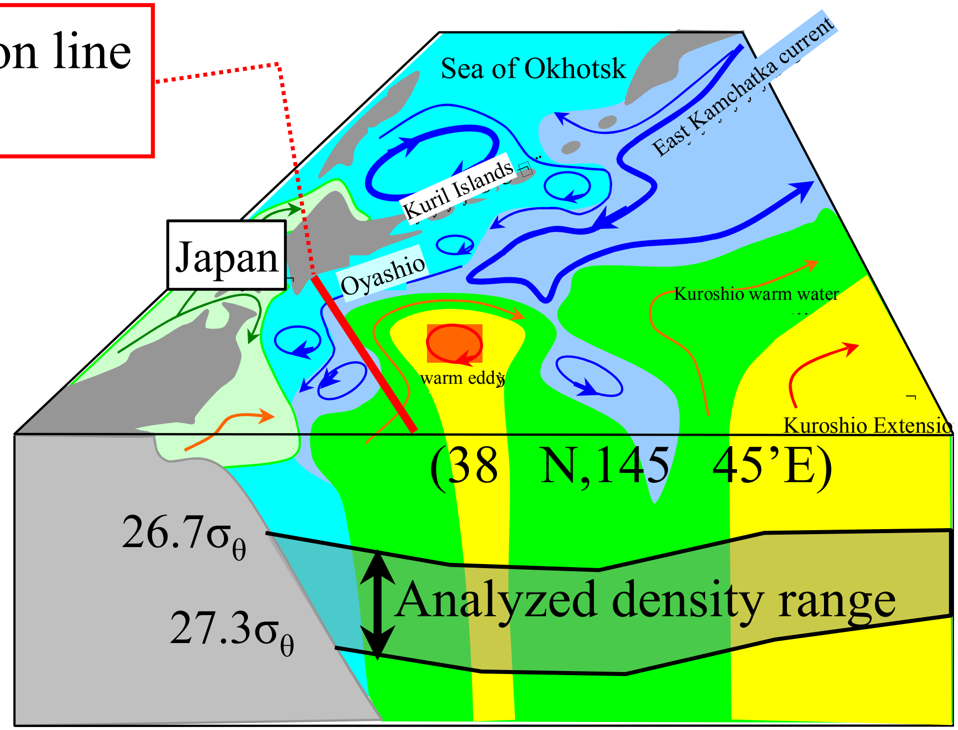
Data CTDO data of a repeat observing section called OICE

Oyashio Intensive observation line off Cape Erimo OICE

Four seasonal cruises in 2001:

- WK0101/ Jan.-Feb. 2001
- WK0104/ Apr. 2001
- TR0108/ Aug.-Sep. 2001
- WK0111/ Nov. 2001

*WK=R/V *Wakataka-maru*
TR= R/V *Torishima*



Multiple tracer analysis

Non-negative least square method for over-determined equations

Assumption

The mixed water is formed by an isopycnal mixture among three source waters with ratio of :

Okhotsk Sea: E. Kamchatka: Kuroshio waters= $r_1 : r_2 : r_3$

Equations

When temperature, salinity, dissolved oxygen and potential vorticity are denoted as ($\theta(\rho)$, $S(\rho)$, $X(\rho)$, $Q(\rho)$) for the observed mixed water and ($\theta_i(\rho)$, $S_i(\rho)$, $X_i(\rho)$, $Q_i(\rho)$) for the source waters at density ρ (i=1:Okhotsk Sea water, 2 E. Kamchatka, 3: Kuroshio components)

Mixture of temperature : $r_1 \bullet \theta_1 + r_2 \bullet \theta_2 + r_3 \bullet \theta_3 = \theta$ (1)

--------- of salinity : $r_1 \bullet S_1 + r_2 \bullet S_2 + r_3 \bullet S_3 = S$ (2)

------ of dissolved oxygen: $r_1 \bullet X_1 + r_2 \bullet X_2 + r_3 \bullet X_3 = X$ (3)

------ of potential vorticity: $r_1 \bullet Q_1 + r_2 \bullet Q_2 + r_3 \bullet Q_3 = Q$ (4)

(Danielsen 1990, Haynes and McIntyre 1990)

Condition

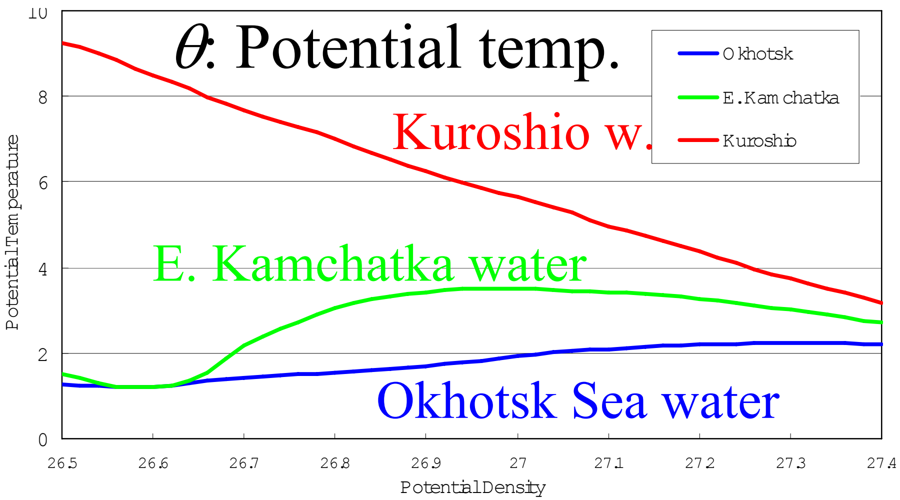
- Summation of mixing ratios =1 : $r_1 + r_2 + r_3 = 1$ (5)
- Mixing ratio cannot be negative: $r_1 \geq 0$, $r_2 \geq 0$, $r_3 \geq 0$ (6)

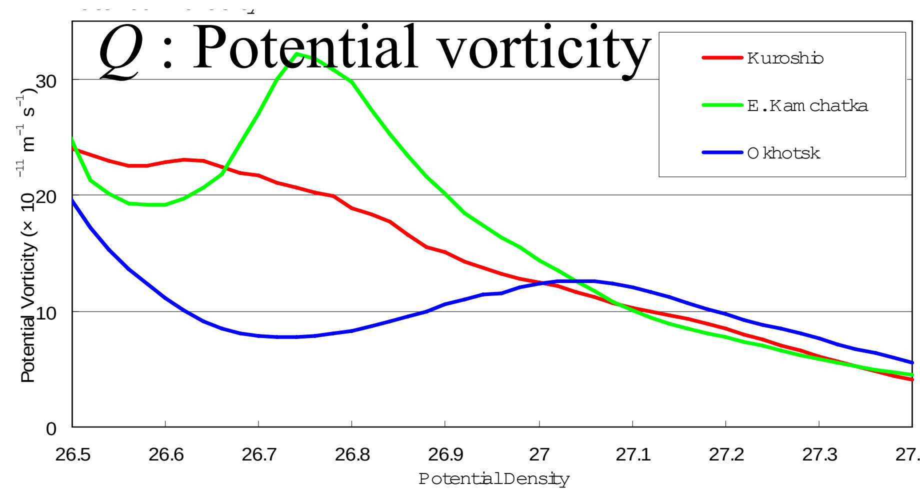
Solution

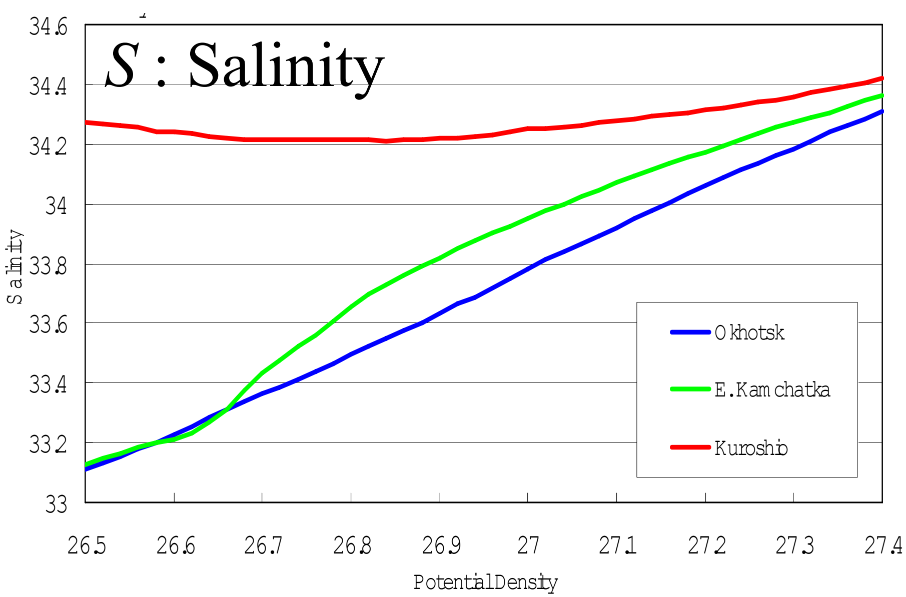
We normalize eqs. (1)-(4) by observation errors in each tracer and standard deviations in the source water variance, and then numerically solve the equations with a least square method on conditions (5) and (6).

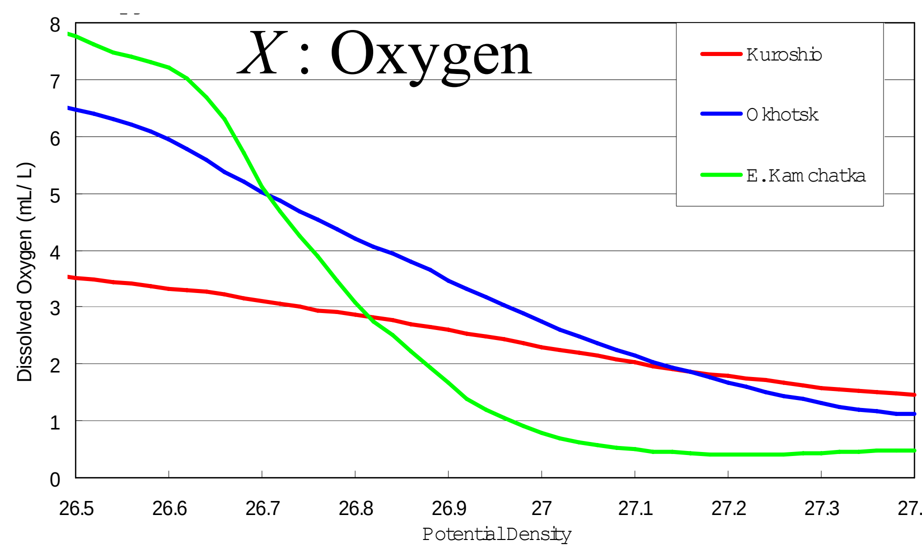
Source water profiles composed from the WOCE data archives etc.

- Okhotsk sea water: Composed from the data near Bussol's Strait in the Okhotsk Sea.
- East Kamchatka w.: Data where the water flows southward east of Kamchatka Pen.
- Kuroshio w. : Data on 137°E and off Boso Pen. These are isopycnal average.

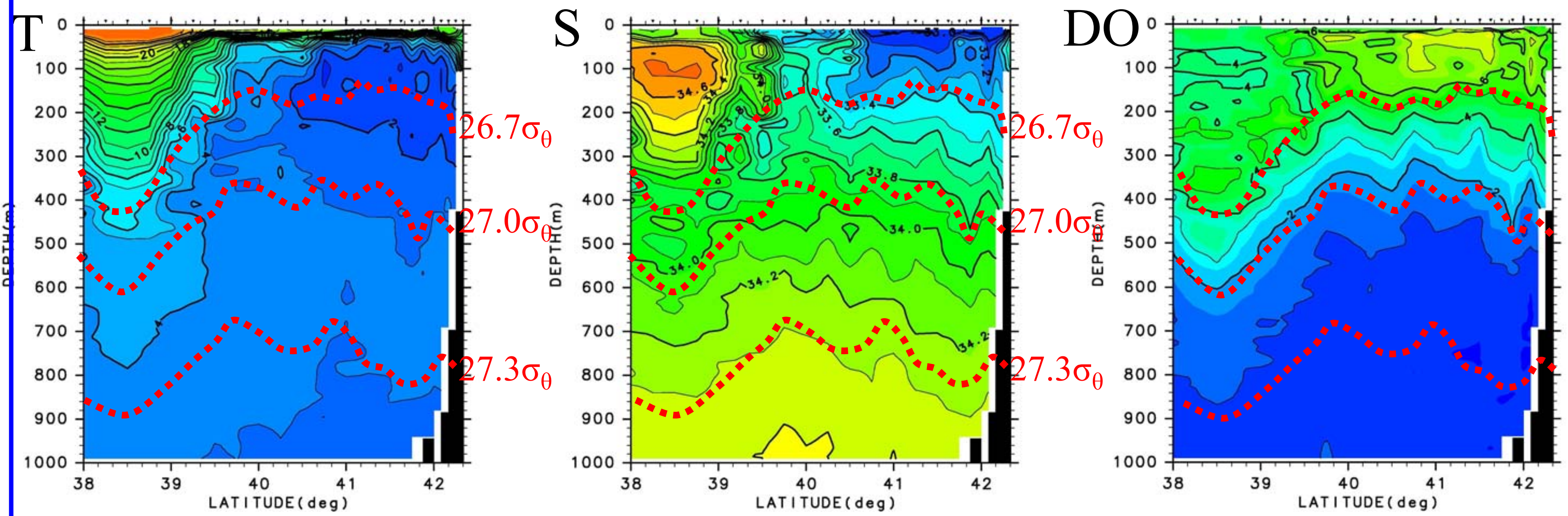






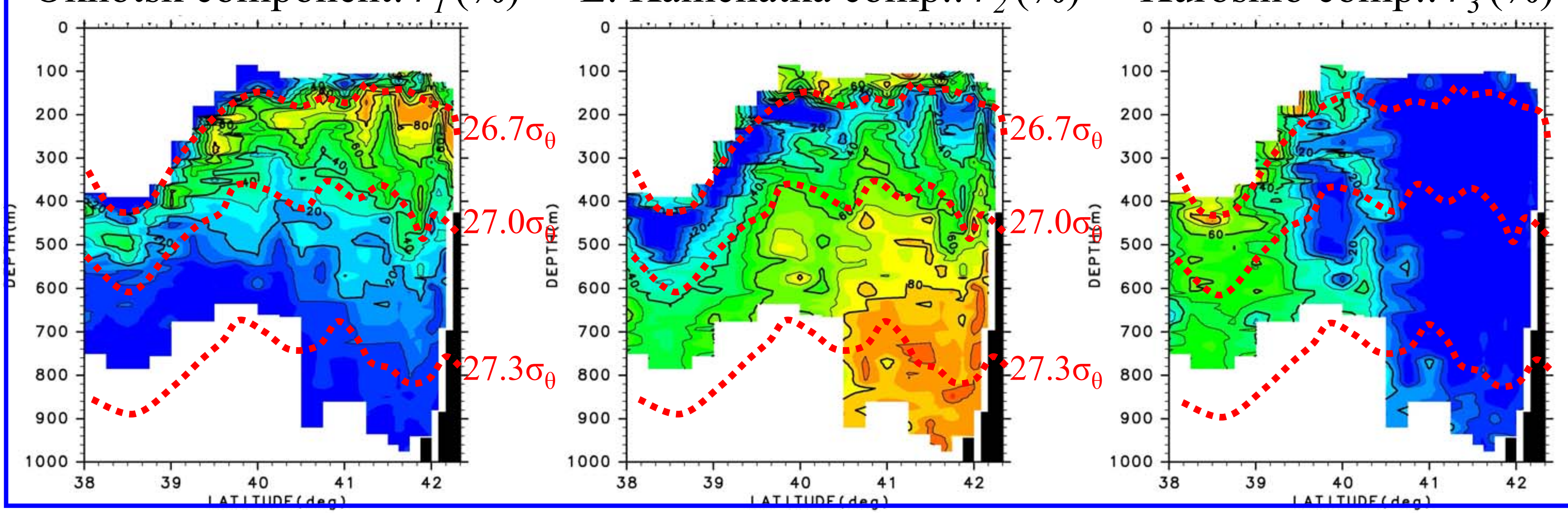


Calculation example: OICE data in TR0108/ Vertical sections of T, S and DO

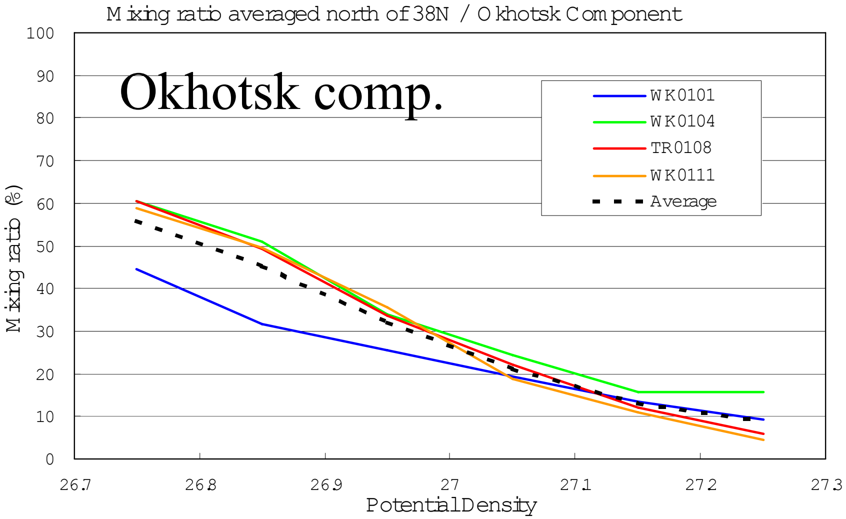


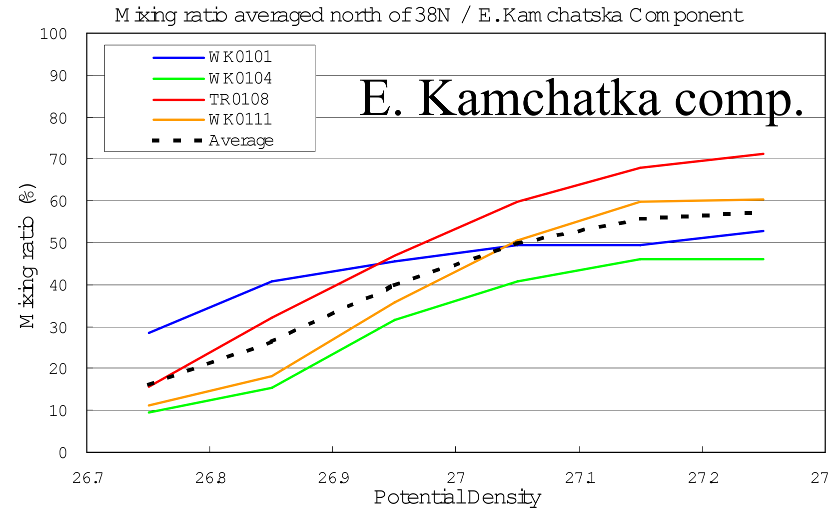
Calculation results of mixing ratio

Okhotsk component: r_1 (%) E. Kamchatka comp.: r_2 (%) Kuroshio comp.: r_3 (%)



Results: average mixing ratio north of 38°N on OICE





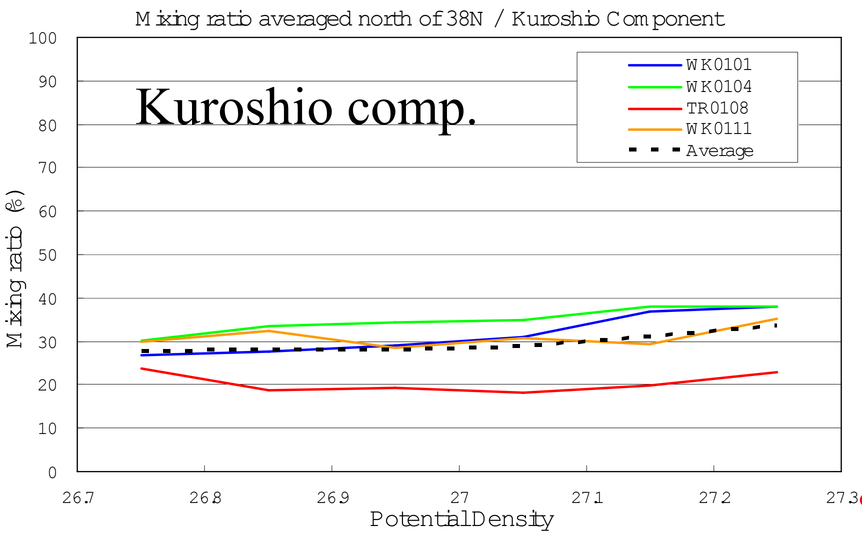


Fig. Average mixing ratios for density in each cruise

Table. Annual mean of the mixing ratios

Layers	Okhotsk	E.. Kamch	Kuroshio
26.7-26.8	56.1	16.2	27.6
26.8-26.9	45.3	26.6	28.0
26.9-27.0	32.2	40.0	27.8
27.0-27.1	21.2	50.1	28.7
27.1-27.2	13.1	55.8	31.0
27.2-27.3	8.8	57.6	33.5
Average	29.5	41.1	29.4

- Okhotsk Sea water component is seen mainly at 26.7-26.9 σ_θ, while E. Kamchatka comp. is seen more at densities denser than 27.0 σ_θ.
- Kuroshio comp. seem less density-dependent.

Transport components north of 38N across OICE (1500dbar reference, positive northeastward)

0.1σ -thickness transport north of 38N / Okhotsk Component

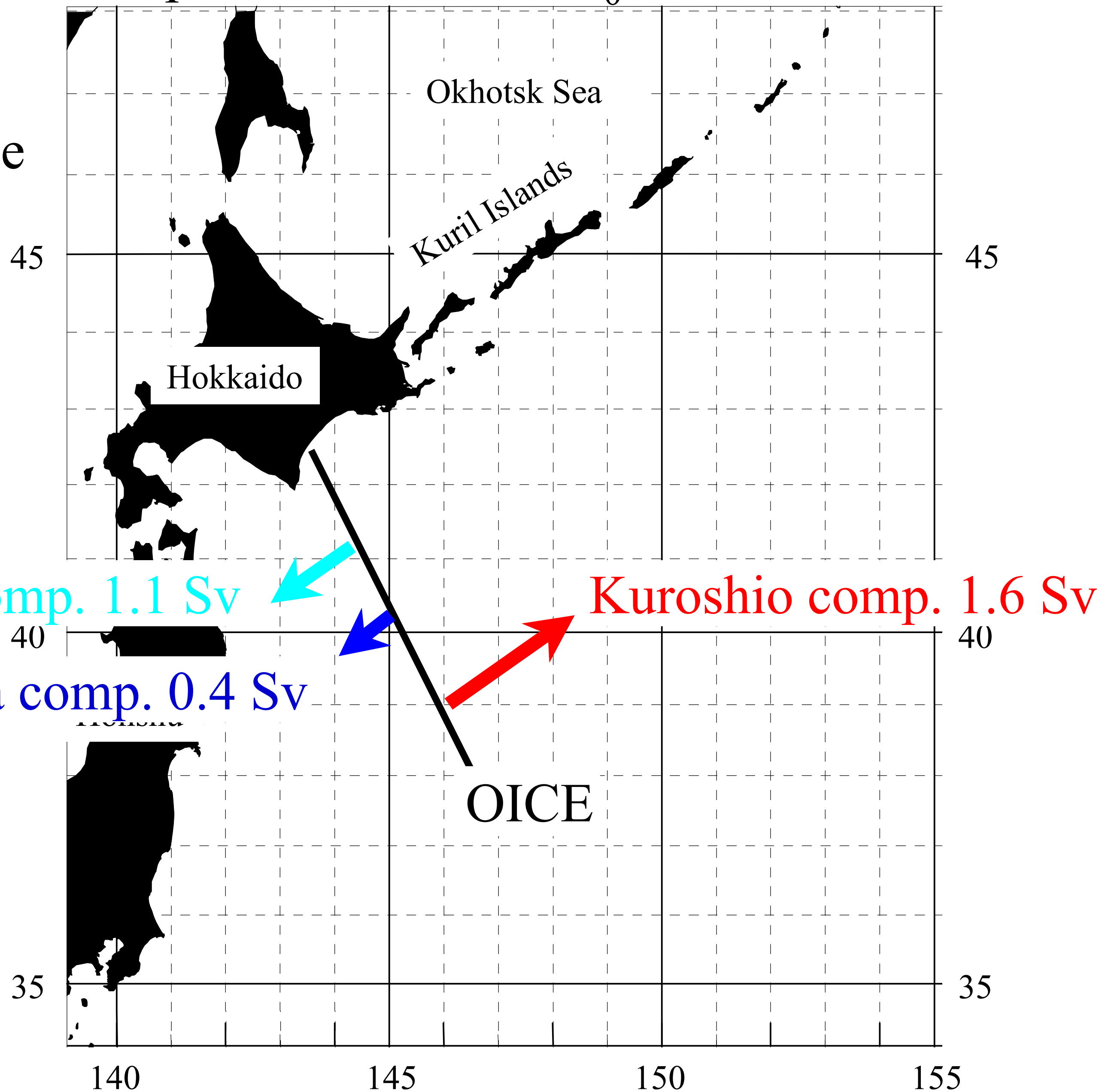
0.1σ -thickness transport north of 38N / E. Kam. Component

The annual mean of the transport components in an isopycnal layer 26.7-27.3σ_θ :
Okhotsk comp.: 1.1 Sv, E. Kamchatka comp.: 0.4 Sv southwestward,
Kuroshio comp.: 1.6 Sv northeastward.

Layers	Total	Okhotsk	E.Kamch.	Kuroshio
26.7-26.8	-0.09	-0.50	0.03	0.38
26.8-26.9	0.04	-0.23	-0.07	0.33
26.9-27.0	0.09	-0.15	-0.02	0.26
27.0-27.1	0.08	-0.11	-0.07	0.27
27.1-27.2	-0.07	-0.10	-0.17	0.20
27.2-27.3	-0.02	-0.05	-0.08	0.11
Total	0.02	-1.14	-0.39	1.55

Annual mean transports in 26.7-27.3 σ_θ across OICE

*1500 dbar reference
*1 Sv = 10^6 m^3/s



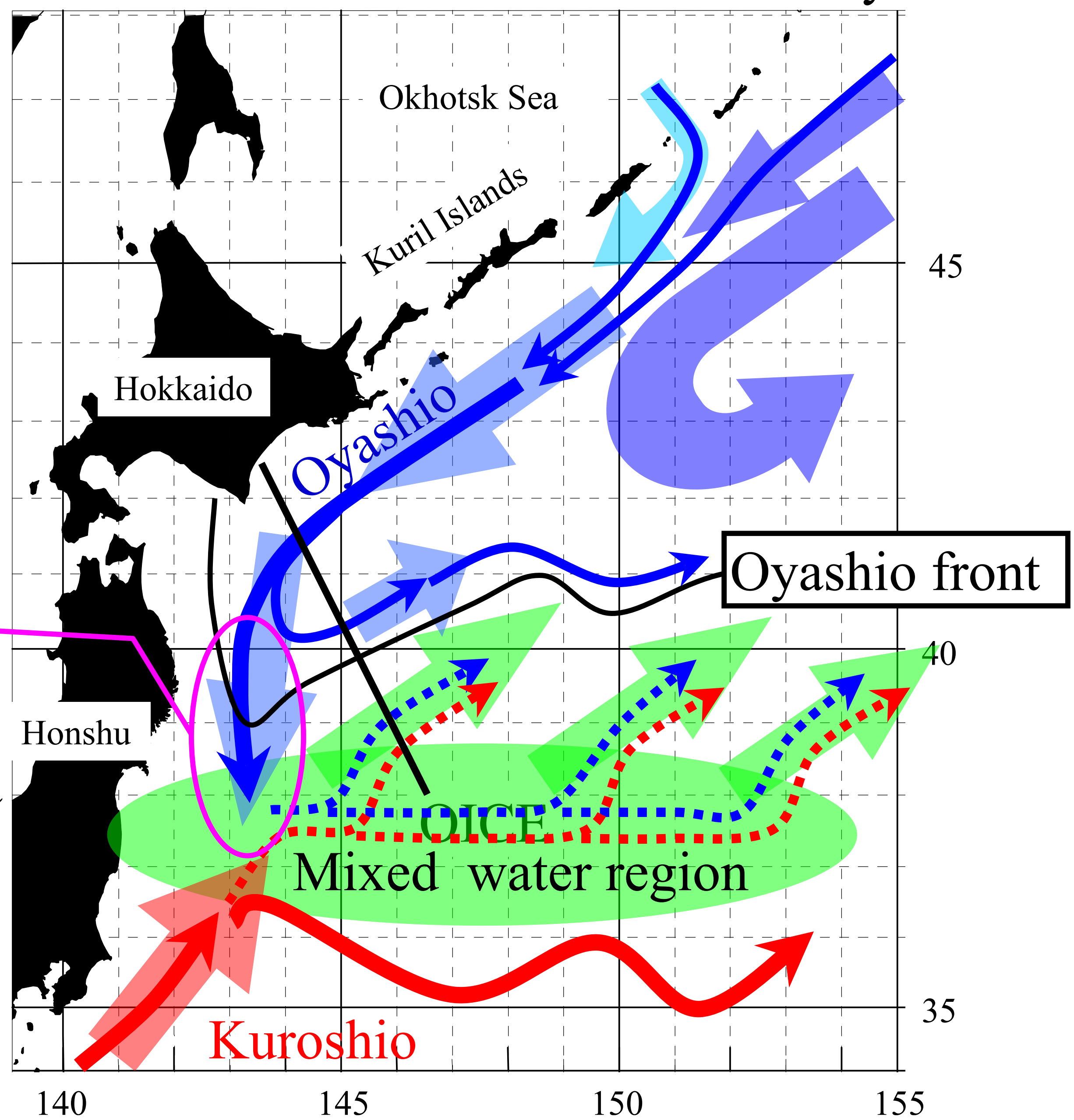
=> What do these values mean??

We have to know the oceanographic location of OICE

We want to know this transport!

Including:
Okhotsk/E. Kamchatka components and their seasonal variation

Schematic circulation in intermediate layers



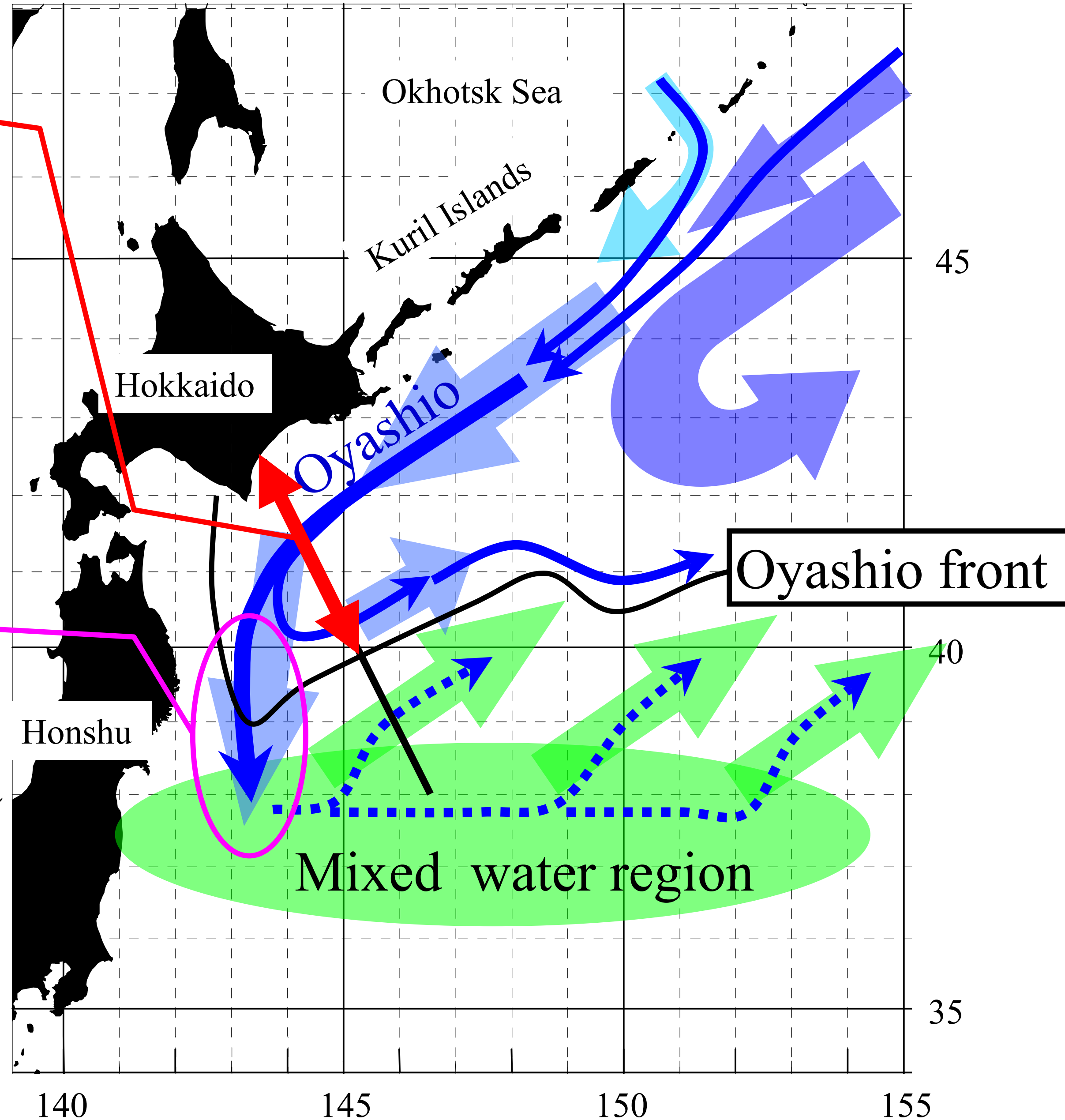
How can we calculate the transport components contributing to NPIW formation?

If we integrate only in the Oyashio area;

we can obtain the transport components which contribute to the new NPIW formation:

This transport

Including:
Okhotsk/E. Kamchatka components and their seasonal variation



Oyashio area definition:

Temperature at 100m depth ≤ 5 °C (the blue area in lower panels).

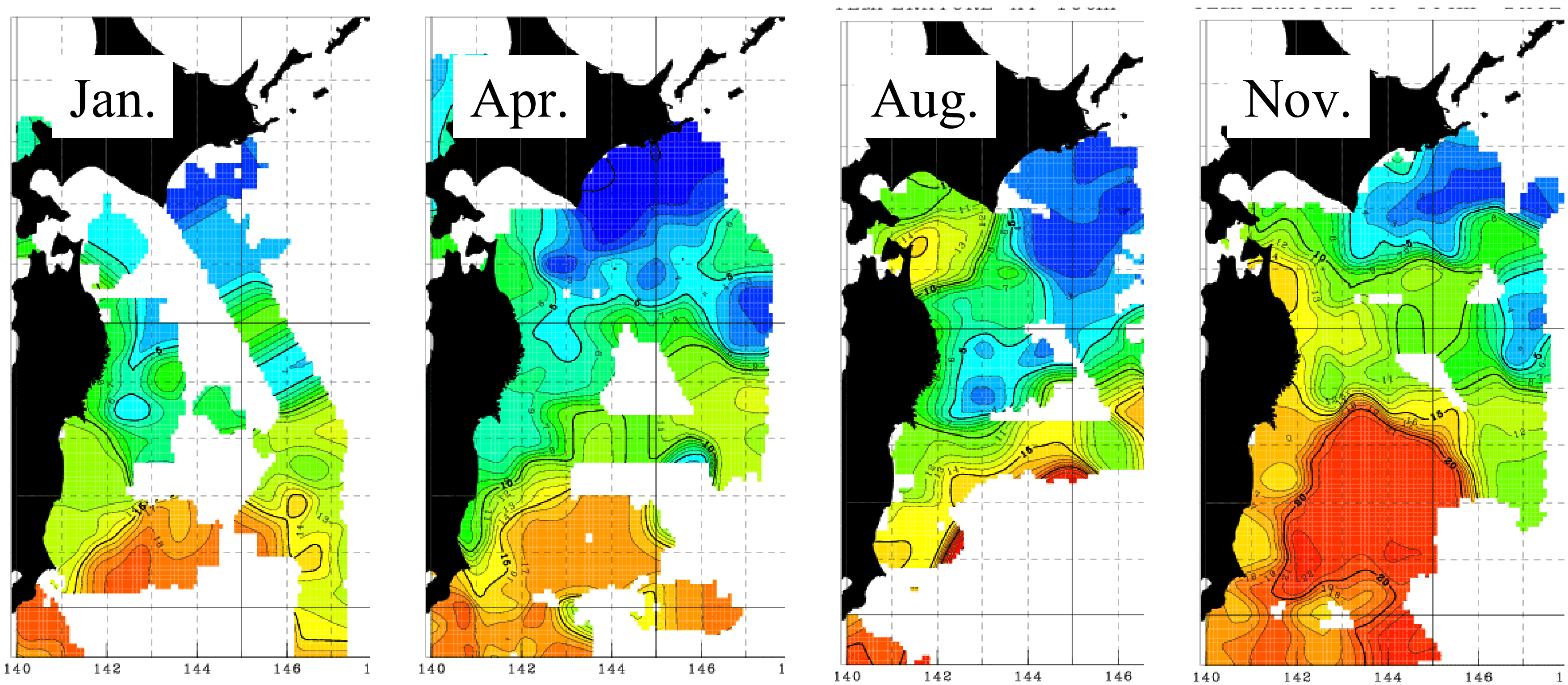
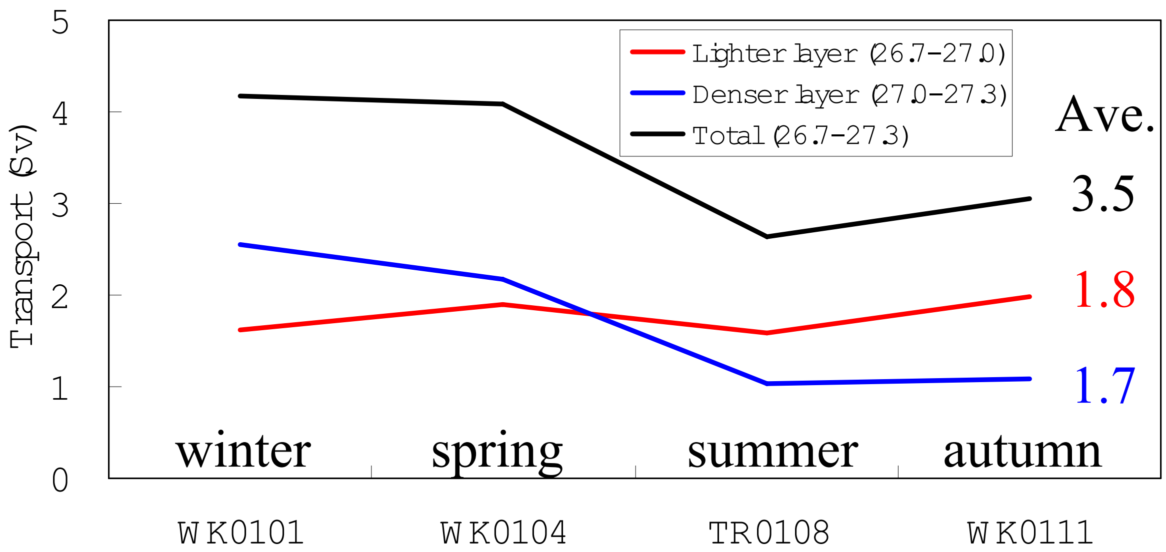


Figure. Temp. at 100 m depth in Jan., Apr., Aug. and Nov. 2001.

Okhotsk and East Kamchatka transport components integrated in the Oyashio area

Okhotsk comp. where $T_{100} \leq 5$ °C (positive southwestward)

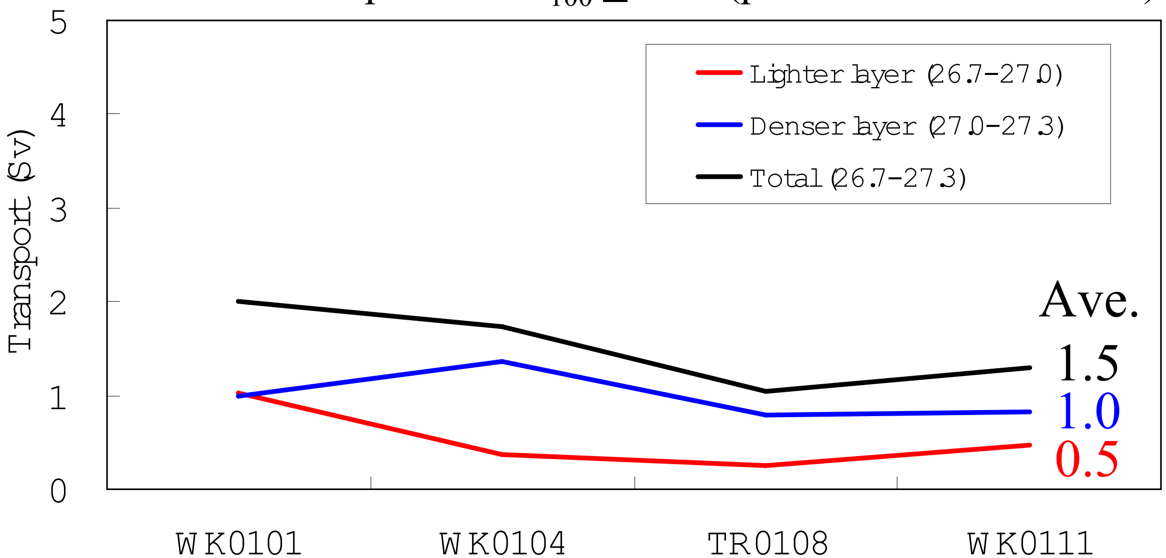


<Okhotsk (Ok) component>

- Annual mean transport in 26.7-27.3σ_θ = 3.5 Sv.
- There is a clear seasonal signal in a denser layer 27.0-27.3σ_θ.
- The transport in a lighter layer 26.7-27.0 σ_θ is almost constant.

=> The Okhotsk component is larger in winter to spring.

E. Kamchatka comp. where $T_{100} \leq 5$ °C (positive southwestward)



<E. Kamchatka (EK) comp.>

- Annual mean transport is smaller than Okhotsk comp. (1.5 Sv, Ratio of Ok: EK=7:3)
- The summer EK transport in a lighter 26.7-27.0 σ_θ is quite small (0.3 Sv).

=> The E. Kamchatka comp. is larger in winter to spring.

Results

We applied a multiple tracer analysis to see the variation of NPIW source waters:

<Spatial distribution of each mixing ratio>

(1) The Okhotsk comp. is seen at lighter densities (especially 26.7-26.9σ_θ), while E. Kamchatka comp. increases with increasing density.

(2) It seems that the Kuroshio component distribution isn't related to density so much (it seems to depend on whether a warm eddy exists or not).

<Subarctic transport components in the Oyashio area>

(1) The Okhotsk comp. is relatively larger than E. Kamchatka comp. in the net southwestward Oyashio transport in annual average (ratio of Ok: EK =7:3).

(2) Both Okhotsk and E. Kamchatka components have a seasonal signal: Their southwestward transports have a maximum in winter and minimum in summer.

=> The outflow from the Okhotsk Sea has a seasonal variation!

Itoh et al. (2003, JGR): The ratio of the Okhotsk and E. Kamchatka component in the Oyashio southward flow (opposite to this study).

Table 7. Mixing Ratios of Okhotsk Sea Intermediate Water (OSIW) and the Western Subarctic Water (WSAW) to Form Oyashio Intermediate Water (OYIW)

	WSAW	OSIW
26.8 σ_0	0.60	0.40
26.9 σ_0	0.57	0.43
27.0 σ_0	0.63	0.37

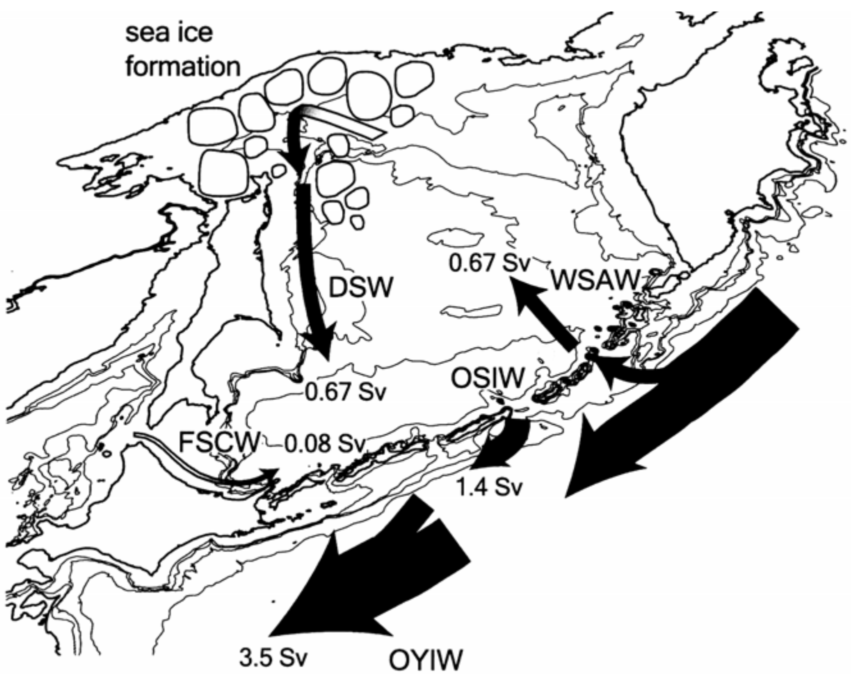
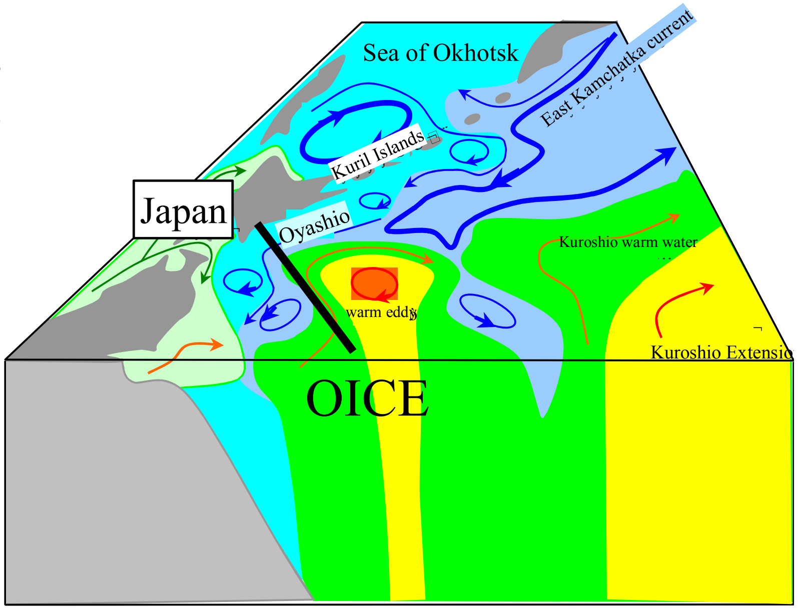


Figure 14. Schematic illustration for the formation of Okhotsk Sea Intermediate Water (OSIW). Production rates and volume transports of Dense Shelf Water (DSW), Forerunner of Soya Warm Current Water (FSCW), Western Subarctic Water (WSAW), Okhotsk Sea Intermediate Water (OSIW), and Oyashio Intermediate Water (OYIW) are presented at densities from 26.75 to 27.05 σ_θ. Line thicknesses are qualitatively related to the magnitude of the volume transports.



The subarctic main stream might turn eastward in the east of OICE?

The method to obtain the least-square solutions in these equations

Matrices

Expressing Eqs. (1)   (4) as matrices:

$$\underbrace{\begin{pmatrix} \theta & \theta_2 & \theta_3 \\ S_1 & S_2 & S_3 \\ X_1 & X_2 & X_3 \\ Q_1 & Q_2 & Q_3 \end{pmatrix}}_{\equiv \mathrm{A}} \underbrace{\begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix}}_{\equiv x} = \underbrace{\begin{pmatrix} \theta \\ S \\ X \\ Q \end{pmatrix}}_{\equiv \mathrm{B}}$$

i.e. $\mathrm{A}x\text{-}\mathrm{B} = O$ (7)

(O: Zero matrix)

Normalize

Defining a diagonal matrix W with RMS ν of each tracer's observation error and variation in the used station data for the source waters in order to lessen the difference among the tracers' error and variation.

$$\mathrm{W} \equiv \begin{pmatrix} \nu(\theta) & & \cdots O \cdots & \\ & \nu(S) & & \\ & & \nu(X) & \\ \cdots O \cdots & & & \nu(Q) \end{pmatrix}$$

Multiply eq. (7) by W in left side

$\mathrm{W}(\mathrm{A}x\text{-}\mathrm{B}) = O$ (8)

Fitting

Searching the best solutions $\boldsymbol{x}$ numerically by minimizing the error of (8): $\mathrm{L}=|\mathrm{W}(\mathrm{A}x\text{-}\mathrm{B})|^2$ on condition of (5) and (6)

Integrate the subarctic transport components only in the Oyashio area

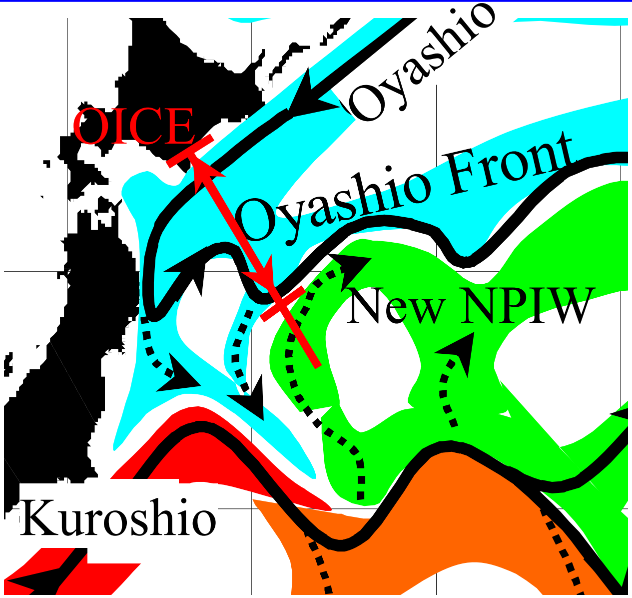
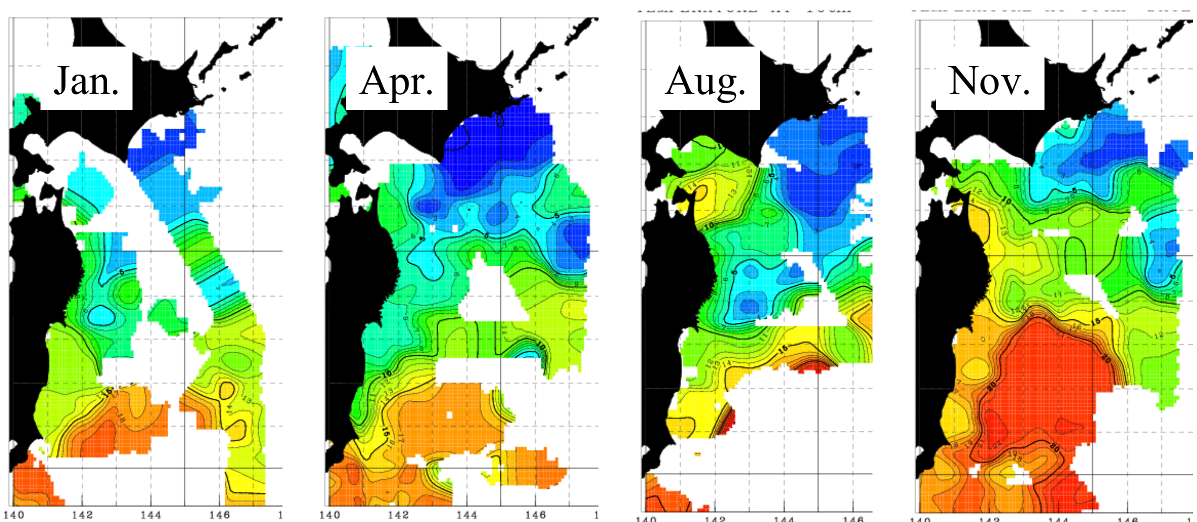


Fig. Schematic representation of intermediate circulation near Japan

- In order to find the net transport components contributing to the new NPIW formation because the observation line OICE cuts through a part of new NPIW formation area.
- We'll examine the seasonal variation in the two subarctic components (Okhotsk and E. Kamchatka components) integrated in the Oyashio area.



The Oyashio area is defined as the area with T ≤ 5 °C at 100m depth (the blue area in left panels).

Figure. Temp. at 100 m depth in Jan., Apr., Aug. and Nov. 2001.