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水産海洋研究

Water mass structure in the spawning area of walleye pollock (*Theragra chalcogramma*) on the Pacific coast of southern Hokkaido, Japan

Itsuka YABE[1], Akira KUSAKA[2], Tomonori HAMATSU[3],
Tomonori AZUMAYA[3†] and Akira NISHIMURA[4]

Relationships between physical environmental factors (temperature, salinity and depth) and the formation of the spawning area of walleye pollock (*Theragra chalcogramma*) off the North Pacific coast of Hokkaido, Japan were examined. Water temperature inside and outside of Funka Bay decreased from January to March and especially in Hidaka Bay because of the Coastal Oyashio Water (COW) intrusion into the surface layer. From quotient analysis, mean spawning environmental conditions of walleye pollock were 4.43 (SD=2.04)°C, and a salinity of 33.28 (SD=0.42), both are typical of the water mass of Oyashio Water (OW). The spawning area moved anti-clockwise from Tomakomai to the mouth of the Tsugaru Strait during the spawning period. Water mass which eggs mainly experienced in the sea surface was OW in January and February, and COW in March. The duration to hatch was from 8 to 20 days in Tsugaru Warm Water (TW), from 15 to 25 days in OW and 25 days or more in COW. We conclude that the relative distribution of water masses affects the location of the spawning area and subsequently the rate of development of the eggs. Finally, we propose a practical method to estimate the spawning area of walleye pollock using the physical environment.

Key words: walleye pollock, eggs, spawning environment, Coastal Oyashio, Oyashio, Tsugaru Warm Current

Introduction

Walleye pollock (*Theragra chalcogramma*) are broadly distributed throughout the North Pacific, including the Sea of Japan, Okhotsk Sea, and Pacific Ocean around northern Japan. In Japan, the largest concentrations are found along the Pacific coast from Hokkaido to the Tohoku area (Tsuji, 1989), and this Pacific stock is one of the most important fishery resources in this area. They are distributed on the shelf and shelf break to about 300 m in depth. The major spawning area of this stock is located around the mouth of Funka Bay, and additional spawning areas are distributed on the Pacific coast of southeastern Hokkaido (Doto) and off the Tohoku region (Fig. 1). The spawning season in Funka Bay is from early December to mid March (Maeda et al., 1976; Wakabayashi et al., 1990). Eggs of walleye pollock have been sampled mostly at the sea surface although the spawning depth is around 100–200 m (Kamba, 1977). Since fertilized eggs are positively buoyant, they rise up from their deep spawning depth to the sub-surface layer (Nakatani and Maeda, 1984; Kendall et al., 1994), and the ocean conditions, e.g. February sea surface temperature, af-

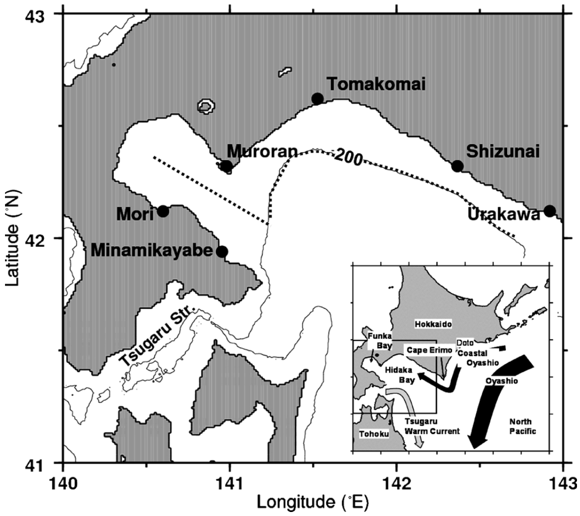

Figure 1. Map of study area with the bathymetric contour of 200 m (thin gray line). Thick dotted line indicates the position of the vertical section shown in Fig. 5. In the inset square is drawn a schematic view of current systems around the study area.

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[1] Japan NUS Co. Ltd., Loop-X Bldg., 7F 3–9–15 Kaigan, Minato-ku, Tokyo 108–0022, Japan

[2] National Research Institute of Fisheries Science, Fisheries Research Agency, 2–12–4 Fukuura Kanazawa, Yokohama, Kanagawa 236–8648, Japan

[3] Hokkaido National Fisheries Research Institute, 116 Katsurakoi, Kushiro, Hokkaido 085–0802, Japan

[4] Seikai National Fisheries Research Institute, Fisheries Research Agency, 1551–8 Taira-machi, Nagasaki, Nagasaki 851–2213, Japan

[†] azumaya@fra.affrc.go.jp

fects their following recruitment (Funamoto, 2007).

Wind-induced currents generated by predominant northwesterly winds in winter play an important role in the transport of eggs/larvae into Funka Bay and its adjacent area (Shimizu and Isoda, 1997). Eggs of walleye pollock are transported into Funka Bay and larvae and juveniles remain in the bay until the first summer. Some evidence has revealed that it is advantageous for survival of eggs and larvae of walleye pollock to remain in Funka Bay where their food production is enhanced (Ohtani and Kido, 1980; Kendall and Nakatani, 1992). Using acoustic and trawl-surveys, Honda et al. (2004) showed that juvenile walleye pollock migrate from the spawning area around Funka Bay to the nursery grounds in the Doto area along the Pacific coast of Hokkaido. Nishimura et al. (2007) and Shida and Nishimura (2002) estimated the hatch-date of juvenile walleye pollock sampled in the Doto area in August and September, being coincident with the known hatching period around the major spawning area in Funka Bay. They suggested that juveniles in the Doto area originated mostly from the Funka Bay spawning population. Hattori et al. (2006) showed that late hatching fish originating from Funka Bay were transported to the Tohoku area by the strong coastal branch of the Oyashio Current.

The ocean environment along the Pacific coast of southern Hokkaido shows complex water mass distributions due to the coexistence of cold and low salinity subarctic water masses (Oyashio Water and Coastal Oyashio Water) and warm and high salinity water (Tsugaru Warm Water) (Fig. 1). Ohtani (1971) described that the Tsugaru Warm Water (TW) occupies Funka Bay in winter and except for the bottom layer the Coastal Oyashio Water (COW) intrudes into Funka Bay in spring. In summer, the Surface Water (SW) occurs near the sea surface and the Oyashio Water (OW) occupies under the thermocline and TW intrudes into the northern part of Funka Bay through the intermediate layer during autumn. COW and TW mainly occur in Hidaka Bay during spring (Shimizu and Isoda, 2001). The ocean environment in this area varies markedly as mentioned above. Kono et al. (2004) showed that the interannual variations of the distribution of COW were considerably large. Thus, it is speculated that the spawning area also varies interannually due to the ocean conditions. Nakatani and Maeda (1981) noted that the walleye pollock spawning migration was affected by the ocean conditions. However, there has been no study to examine the relationship between the spawning area and the water mass structure. On the other hand, Euler-Lagrangian experiments have been carried out to examine the nursery environment and transport process of eggs using the output of a numerical ocean model (Shimizu and Isoda, 1997). However, to enable accurate modeling, prediction of the spawning area for the initial position of Euler-Lagrangian experiments is needed. The purpose of the present study is thus to examine the relationships between the spawning area and the physical environment, and these water masses and the development of eggs using monthly mean data and to propose a method to estimate the spawning area of walleye pollock.

Materials and Methods

In consideration of the importance of the recruitment process of walleye pollock, egg and larval distribution surveys with oceanographic observations have been conducted by the Hokkaido National Fisheries Research Institute from January to March, 1981–2006. We analyzed the data sets where ring net observations of egg abundance and hydrographic measurements were simultaneously carried out (Table 1). To describe the temporal variation of egg distribution and physical environment, data from the area between 41°N–43°N, 140°E–143°E were stratified into 10′ latitude by 10′ longitude areas (10′×10′ grids), and by month from January to March because of the difference in the number of sampling stations. Data were abundant in Funka Bay and the shelf area near the mouth of Funka Bay in January and February. Although the range of observations extended to the Doto area, the observations in the Doto area were only about a fifth of the number around Funka Bay. We therefore analyzed the data obtained in and around Funka Bay only.

Eggs of walleye pollock were collected by vertical hauls of a ring net (net mouth diameter: 80 cm; net length: 250 cm; net mesh: 0.6 mm) from the bottom. Maximum length of the wire warp of the ring net was 500 m. Immediately after the collection, samples were fixed in 5–10% formalin-seawater solution; afterwards, the eggs were sorted and counted. The temporal and horizontal distributions of eggs, which was the average catch of walleye pollock eggs per haul (henceforth referred to as “density”), were calculated for each 10′×10′ grid every month. We divided the embryonic development of eggs into seven stages according

Table 1. Research year, period and number of observation stations of each cruise used in the present study.

Year	Period	No. of stations
1990	January 18–February 1	167
1991	January 18–March 1	404
1992	January 16–February 24	370
1996	January 19–February 19	373
1997	January 27–February 9	136
2003	January 21–March 10	160
2004	January 21–February 21	115
2005	January 19–March 17	166
2006	January 14–March 11	152

to Nakatani and Maeda (1984). Here, stage-1 eggs (ST1) are from fertilization to the blastula stage, and we focused on this stage in the present study. The duration of ST1 is about 1 day from spawning in this season (Nakatani and Maeda, 1984). If they are transported by a current of less than $0.2\,\mathrm{m\,s^{-1}}$ (Rosa et al., 2007) during 1 day, the transported distance from the spawning area is less than 10 miles. Thus, the estimated horizontal distribution of ST1 was assumed as the spawning area of walleye pollock.

Hydrographic measurements by an STD (JFE Advantech Co. Ltd., Japan) were conducted. To understand the physical environment in the spawning season of walleye pollock, hydrographic data from the surface to the seafloor or to the maximum depth of 500 m were gridded horizontally at 10′ grid intervals using Gaussian filter with an *e*-folding scale of 10 km, and were monthly averaged as well as the egg density data. In addition, water mass classification was examined in each grid. Although water mass classification according to Ohtani (1971) is usually applied in Funka Bay, there were water masses that did not fit this classification in the adjacent area of Hidaka Bay. In the present study, water systems were classified into five water mass types on the basis of temperature and salinity using the water mass classifications by Hanawa and Mitsudera (1986) (Fig. 2). According to Hanawa and Mitsudera (1986), water with a temperature less than 2°C and a salinity range from 32.0 to 33.0 was defined as COW, water with a temperature higher than 5°C and a salinity range from 33.7 to 34.2 as TW, and water colder than 7°C, a salinity range from 33.0 to 33.7 and a density lower than $1026.7\,\mathrm{kg\,m^{-3}}$ as OW. Water with a density higher than $1026.7\,\mathrm{kg\,m^{-3}}$ and salinity less than 33.7 or with a temperature less than 5°C and salinity range from 33.7 to 34.2 was classified as the Cold Lower-layer Water (CL). Another water mass was water originally of COW and OW which had been warmed by the sea surface heating and was defined as SW. Sampling data of ST1 as well as temperature and salinity data were combined to examine the spawning environment of walleye pollock.

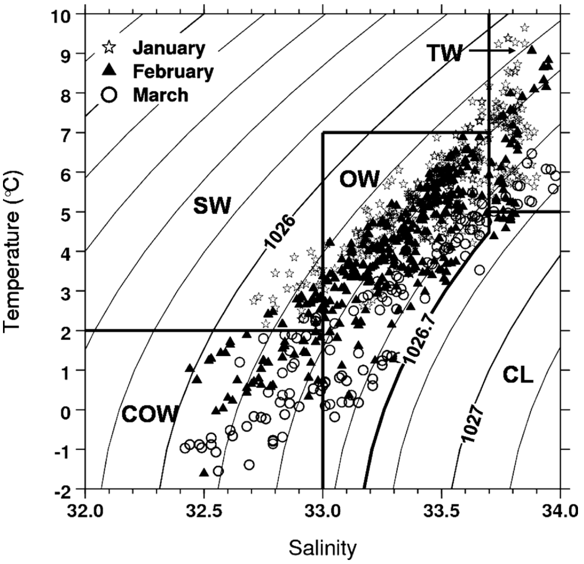


Figure 2. Temperature–salinity relationships at a depth of 150 m. For stations shallower than 150 m, data from depths closest to the sea-floor were used. Isopycnals are drawn as the contours of water density in $\mathrm{kg\,m^{-3}}$. Typical values for Coastal Oyashio Water (COW), Tsugaru Warm Water (TW), Oyashio Water (OW), Surface Water (SW) and Cold Lower-layer Water (CL) are enclosed by the thick lines, according to the definitions of Ohtani (1971) and Hanawa and Mitsudera (1986).

In the present study, temperature-dependent egg developmental time from fertilization was estimated using a function of water temperature based on the Arrhenius' equation (Hattori, 1983; Watanabe T, 1983; Uehara and Mitani, 2004; Oozeki et al., 2007):

$$V(T)=10^{a/(T+273)-b} \qquad (1)$$

where V is the duration [day] to hatch, T is temperature [°C], and a and b are constants. Parameters for a and b are 4735 and 15.8, respectively. The equation was estimated by regression analysis ($n=15$, $r^2=0.99$, $p<0.01$) using data of the egg developmental time from fertilization to hatching with respect to each temperature from -1 to 13°C (Kamba, 1977; Nakatani and Maeda, 1984).

The quotient-rule analysis was applied to assess the preferred ranges of environmental variables for walleye pollock. Each environmental variable, water temperature, salinity and the depth of bottom was assigned a number of classes (c). The quotient value (Qc) of each environmental variable was calculated in each class using the method developed by Twatwa et al. (2005) and Oozeki et al. (2007). The frequency of eggs of ST1 for all sampling stations ($\%\,\mathrm{eggs}_c$) was divided by the frequency of the environmental variable for all sampling stations ($\%\,\text{environmental variable}_c$) as follows:

$$Qc=\frac{\%\,\mathrm{eggs}_c}{\%\,\text{environmental variable}_c} \qquad (2)$$

Only quotient values >1 are considered as signifying positive selection and those <1 indicate avoidance of those environmental classes for spawning.

To estimate the spawning area in each analyzed grid objectively, we propose a Spawning Area Index (*SAI*) the values of which define the suitability for spawning. *SAI* is the product of indexes of three environmental factors (temperature, salinity and depth),

$$SAI(i,j,t)=I_{\mathrm{temp}}(i,j,t)\times I_{\mathrm{sal}}(i,j,t)\times I_{\mathrm{dep}}(i,j,t) \qquad (3\text{-}1)$$

Table 2. Parameters of temperature, salinity and depth for the *SAI* (Spawning Area Index). A_M indicates the mean values and A_{SD} the standard deviations.

	Temperature (°C)	Salinity	Depth (m)
A_M	4.43	33.28	182.67
A_{SD}	2.04	0.42	109.87

Here, $I(i, j, t)$ is the index of each factor assuming a normal distribution and is dimensionless as shown below:

$$I(i, j, t) = \exp\left(\frac{-(A(i, j, t) - A_M)^2}{2 \times A_{SD}^2}\right) \tag{3-2}$$

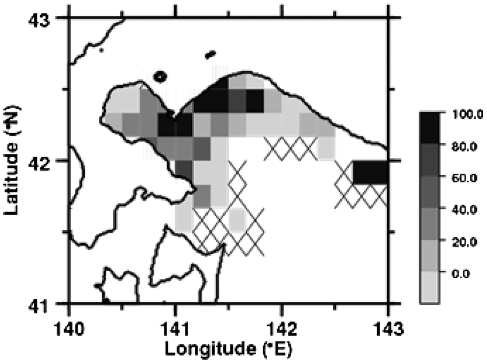
where i and j are the grid numbers in longitude and latitude, respectively, t month, $A(i, j, t)$ the value (temperature, salinity and depth) of each grid and month, A_M is the mean value and A_{SD} its standard deviation (Table 2), and these were derived from the quotient curve. A_M was assumed to be optimum for spawning of walleye pollack. The difference between A_M and $A(i, j, t)$ of each grid was standardized to a value from 0 to 1 as the index. The value of *SAI* also ranges from 0 to 1 and is dimensionless. As the value of *SAI* closes to 1 in a grid, it is possible for the grid to be a spawning area. Since the spawning depth of walleye pollock is known as shallower than 150 m around Funka Bay (Kamba, 1977; Nakatani and Maeda, 1984; Bakkala et al., 1986), we used water temperature and salinity data at 150 m or near the the seafloor as the temperature of spawning depth. Depth data was used from J-EGG 500 (www.jodc.go.jp) and we ignored t of the depth index since t of the depth did not vary within each month.

Results

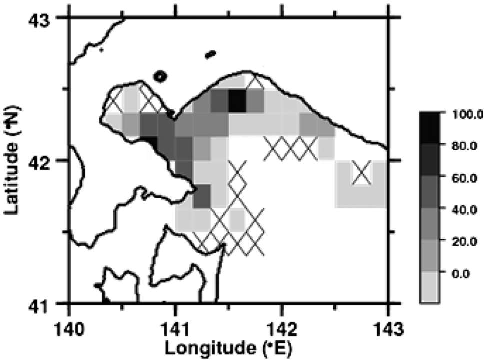
Distribution and density of ST1 and monthly averaged hydrographic conditions

ST1 were abundant around the mouth of Funka Bay and adjacent area from January to March (Fig. 3). The averaged number of ST1 in grids was 46 (number per haul) in January, 25 in February and 12 in March. ST1 were most abundant in January and the density of ST1 decreased to March. In January, ST1 were abundant along the coast. The maximum number of ST1 per haul was 238 around Muroran. In February, ST1 were abundant around Tomakomai and the maximum number was 170. In March, ST1 were abundant around Muroran and the maximum number was 137. The area where ST1 were abundant moved anti-clockwise along the coast from Urakawa around to Tomakomai and Muroran. In January ST1 were distributed throughout Funka Bay. However, ST1 were distributed in only the southern part of Funka Bay in February. In March, few ST1 were caught. In the eastern mouth area of the Tsugaru Strait, ST1 were scarce in January and February although ST1 were sampled there in March.

(a) January



(b) February



(c) March

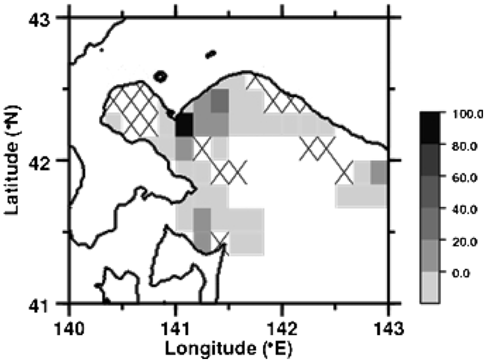


Figure 3. Horizontal distributions of the density of walleye pollock stage-1 eggs (number per haul) in January (a), February (b) and March (c). Crosses show no eggs were sampled.

In January, TW appeared in the inshore area of Funka Bay and around the eastern mouth area of the Tsugaru Strait (Fig. 4). In Funka Bay, water temperature was around 6.0°C. Low-salinity (<33.0) could be seen along the coast

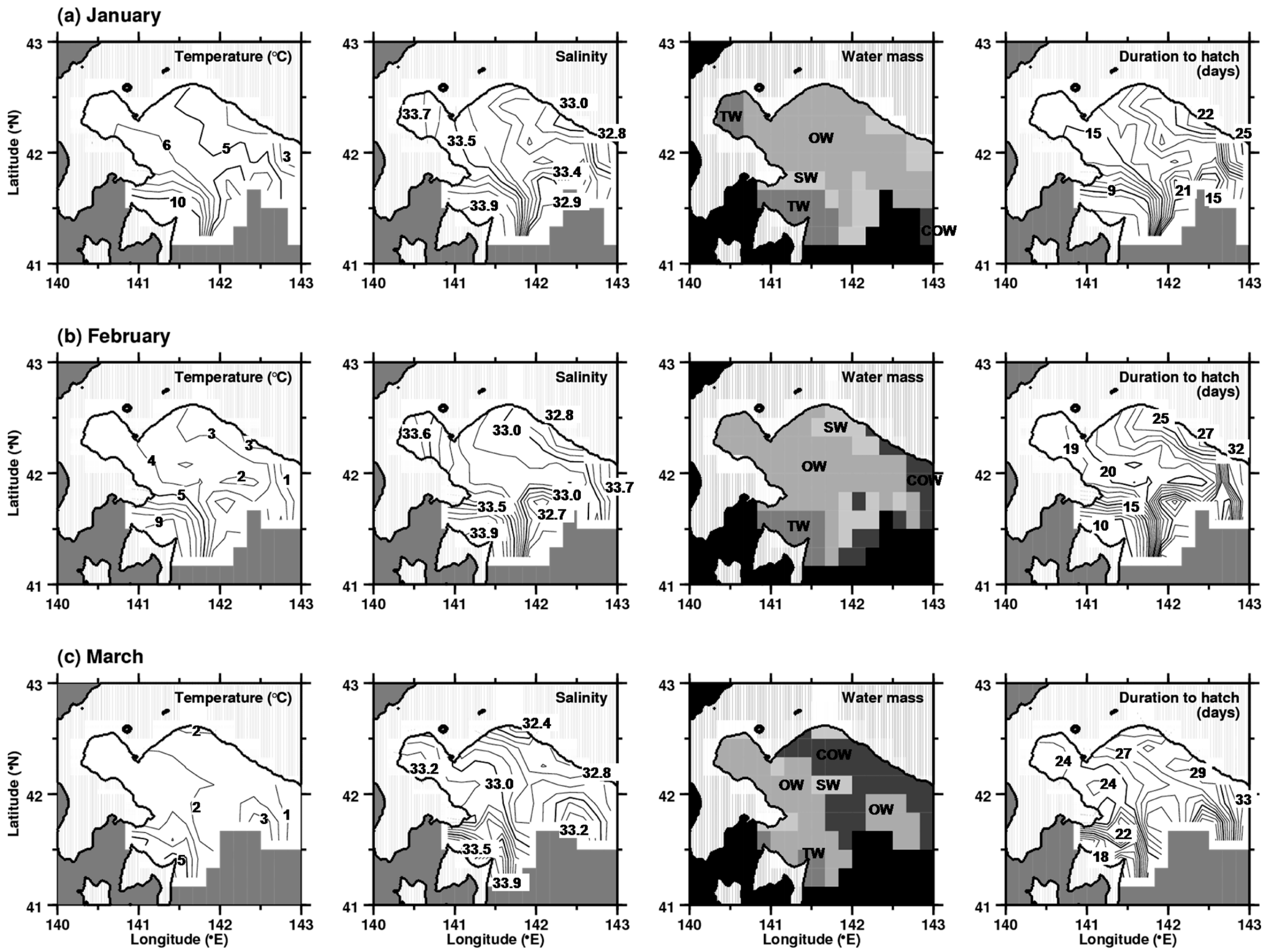


Figure 4. Horizontal distributions of monthly averaged temperature, salinity, water mass and duration to hatch in January (a), February (b) and March (c) at a depth of 10 m.

from Shizunai to Urakawa and offshore in Hidaka Bay. In February, TW still appeared in the eastern mouth area of the Tsugaru Strait. However in Funka Bay, water temperature was around 4.0°C and salinity was lower than TW. COW could be seen along the coast from Shizunai to Urakawa and offshore in Hidaka Bay. In March, water temperature around Funka Bay was about 2.0°C and was the coldest through the period analyzed. COW reached the westernmost longitude around Muroran and extended offshore. In contrast, TW was restricted in the eastern mouth area of the Tsugaru Strait.

In Funka Bay, TW was distributed from the bottom to about 20 m in January (Fig. 5). In February, OW was distributed from the surface layer to a depth of 70 m. In March, TW and CL remained below 50 m in depth and shallower than 50 m in the inner part of the bay. In Hidaka Bay, OW was distributed widely from the surface to a depth of 200 m in January. SW with low salinity water was distributed in the surface layer between Shizunai and Tomakomai and around Urakawa. In February, COW appeared around Urakawa in the surface layer at a depth from 5 to 70 m. SW was distributed in the surface layer from Shizunai to Tomakomai. In March, COW extended to the vicinity of Muroran in the surface layer. TW and CL appeared in the middle layer at a depth from 150 to 200 m and the vertical structure of water mass became complex in March.

Water mass in the spawning area

Walleye pollock mainly spawned in OW and TW in January, February and March (Fig. 2). Walleye pollock also spawned in COW in February and March. The mean water density at the spawning area was 1026.4 kg m^{-3} in January and February, and 1026.6 kg m^{-3} in March. The water density at the spawning area increased with decreasing water temperature. We examined the water mass composition in the spawning area where ST1 appeared (Fig. 6a). We divided the area into five water masses, COW, TW, OW, SW

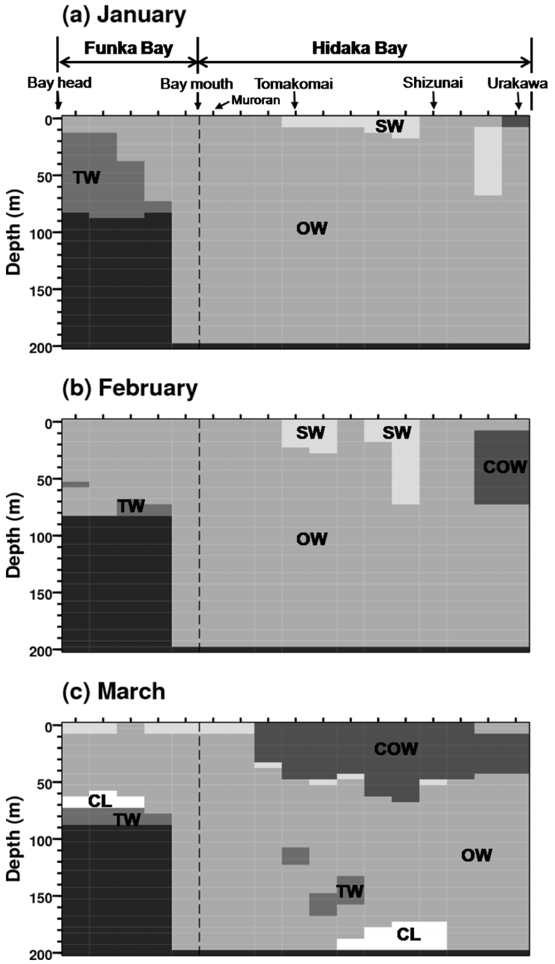


Figure 5. Vertical distributions of water masses for each month along the dashed line shown in Fig. 1.

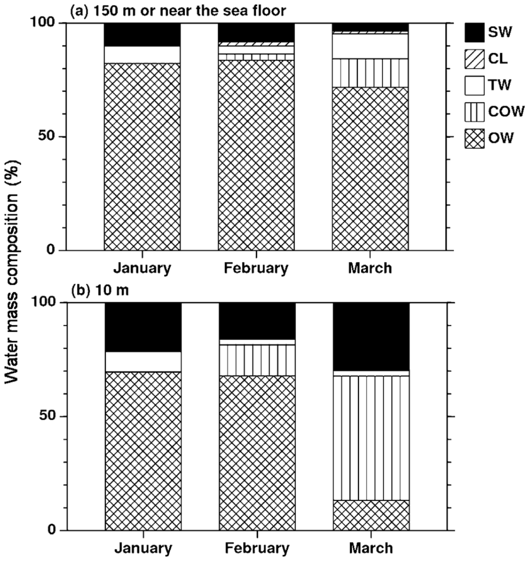


Figure 6. Water mass compositions at the spawning area from January to March. (a) at a depth of 150 m (for stations shallower than 150 m, data from depths closest to the sea-floor were used), (b) at a depth of 10 m.

and CL. In January, February and March, the major water mass at the spawning depth was OW, which occupied about 80% of the water mass, TW which occupied 3–8% and CL which occupied 8%. In March, COW occupied 13% of the water mass. This result indicates that walleye pollock spawned mainly in OW in the spawning season.

When temperature at the depth of 10 m decreases from about 6.0°C in January to less than 2.0°C in March (Fig. 4), and the water density increased, the rising rate of the eggs would change with the exchange of the water mass. Mean density of eggs is 1020–1023 $\mathrm{kg\,m^{-3}}$ (Nakatani and Maeda, 1984), which is less dense than the water at the spawning area. Here, we estimated the rising rate of eggs using Stokes's law expressed by:

$$w = -\frac{2r^2(\rho - \rho_0)g}{9\eta} \tag{4}$$

where w is the rising rate ($\mathrm{m\,s^{-1}}$), r is the radius of the particle (m), ρ is the density of the particle ($\mathrm{kg\,m^{-3}}$), ρ_0 density of the fluid ($\mathrm{kg\,m^{-3}}$), g ($9.8\,\mathrm{m\,s^{-2}}$) acceleration of gravity and η ($0.15\,\mathrm{kg\,m^{-1}\,s^{-1}}$) viscosity. Radius of eggs in Funka Bay is about 0.00075 m (Nakatani and Maeda, 1984). In the cases of water density being 1026.4 $\mathrm{kg\,m^{-3}}$ in January and 1026.6 $\mathrm{kg\,m^{-3}}$ in March, w values are about 0.0031 $\mathrm{m\,s^{-1}}$ and 0.0033 $\mathrm{m\,s^{-1}}$, respectively. Eggs reach the sea surface in March faster than in January. The estimated w values are slightly higher than that of Nakatani's experiment (0.0014 $\mathrm{m\,s^{-1}}$). These upward velocities indicate that eggs reach the surface in one or two days. Therefore, ST1 experienced environmental conditions near the sea surface which may be different from those at the spawning depth.

Water mass composition near the surface at a depth of 10 m is shown in Fig. 6b. In January, the composition of water masses was 70% of OW, 9% of TW and 20% of SW. The difference of environment between spawning depth and sea surface was small in January. In February, the composition of water masses 68% of OW, 14% of COW and 15% of SW. The composition of OW in the surface layer was lower than at the spawning depth. In March, COW was 55%, OW was 15% and SW was 30%. This result indicates that the environment, which ST1 experienced near the surface in March, was likely to markedly change from that of the spawning depth.

The duration to hatch of eggs

Temperature-dependent egg developmental time from fertilization to hatching is shown in Fig. 7. From Equation (1) the relatively low temperatures strongly affected the duration to hatch. For example, if eggs developed at 5.0°C, it

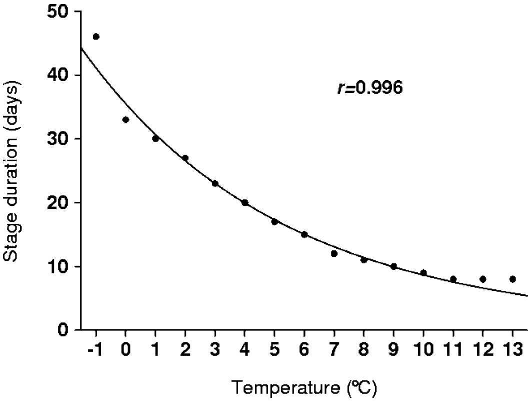


Figure 7. Relationship between temperature and the duration to hatch. Data after Kamba (1977) and Nakatani and Maeda (1984). Solid circles: the results of the experiment, thick line: regression curve calculated by the least-squares method.

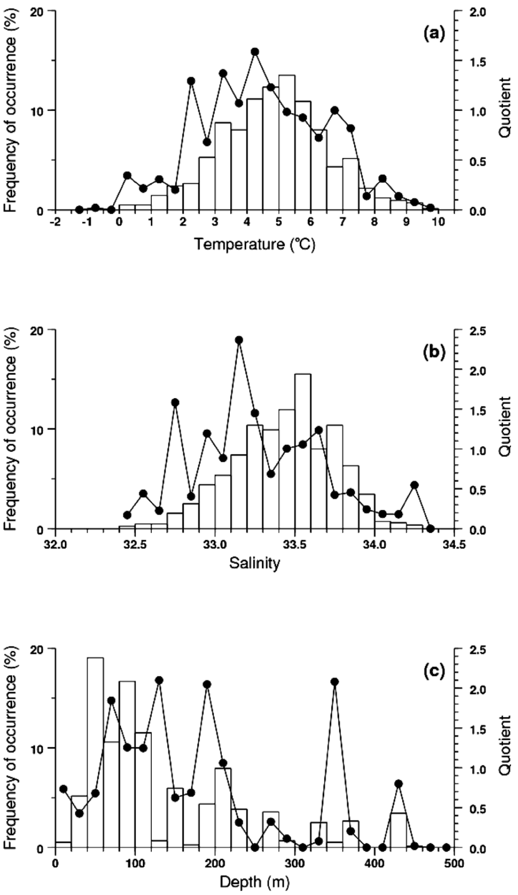


Figure 8. Frequency of occurrence distributions of environmental variables: (a) temperature, (b) salinity and (c) bottom depth. Frequency of occurrence is shown in the histograms. Solid lines are for egg abundance/environment (temperature, salinity and bottom depth) quotients.

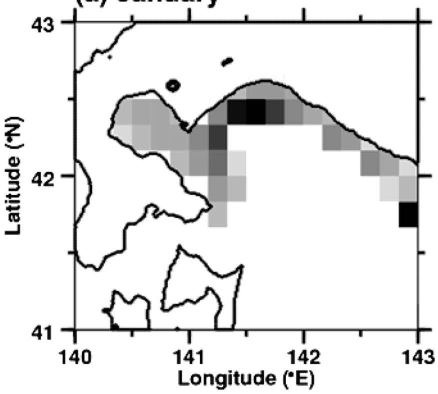
would take about 18 days to hatch. Here, assuming that the variation of water temperature and advection of eggs did not occur, the horizontal distribution of the duration to hatch using equation (1) was calculated every month (Fig. 4). The horizontal distribution of the duration to hatch was similar to the horizontal distribution of the monthly mean water temperature. The duration to hatch became longer as the water temperature gradually decreased. In the eastern part of Hidaka Bay, the duration to hatch was about twice as long as in the eastern mouth area of the Tsugaru Strait from January to March. It takes about 10 days to hatch in the eastern mouth area of the Tsugaru Strait and 1 month in the eastern part of Hidaka Bay in January. Inside and around the mouth area of Funka Bay, the duration to hatch was almost 15 days in January, 20 days in February and 25 days in March. The duration to hatch changed sharply among the different water masses. The duration to hatch required from 8 to 20 days in TW, from 15 to 25 days in OW and 25 days or more in COW. The duration to hatch of eggs which entered in COW was longest of the five water masses.

Relationships between the egg density of ST1 and temperature, salinity and depth

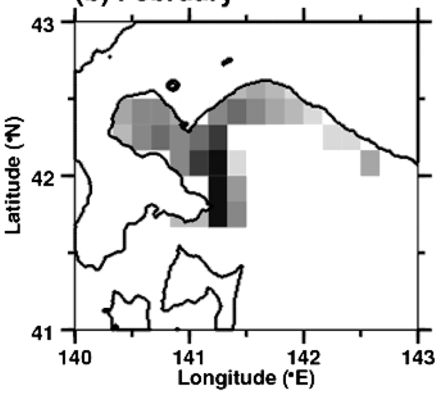
In order to evaluate the environmental conditions in the spawning area, we investigated the relationship between the density of ST1 and water temperature, salinity and depth using the quotient analysis. From the results of the depth quotient analysis, although the highest values of the quotient were found at 4–4.5°C and ST1 were mainly concentrated in water temperature 4.43 ($SD=2.04$)°C, the highest value of occurrence of water temperature was 5–5.5°C (Fig. 8a). The quotient decreased at temperatures less than 2°C or more than 7.7°C. The highest value of occurrence of salinity was 33.6 (Fig. 8b). The highest values of quotient were found in 33.1–33.2 and ST1 were mainly concentrated in salinity 33.28 ($SD=0.42$). The quotient decreased at salinity more than 33.7. ST1 were mainly concentrated in depth 182.67 ($SD=109.87$) m (Fig. 8c), and 80% of ST1 were sampled shallower than 250 m. The highest values of quotient were found at the depth of 110–120 m. The quotients decreased from 220 m with exception of 340–360 m. However, the highest value of occurrence of the depth was found 40–60 m.

Relatively high values of *SAI* moved anti-clockwise which was along the coast from Urakawa to Muroran in January, the mouth of Funka Bay in February and from the mouth of Funka Bay to the eastern mouth of the Tsugaru Strait in March (Fig. 9). This was similar to the distribution of ST1 shown in Fig. 3. There was a significant correlation between the distribution of SAI and that of the observed ST1 ($p<0.01$).

(a) January



(b) February



(c) March

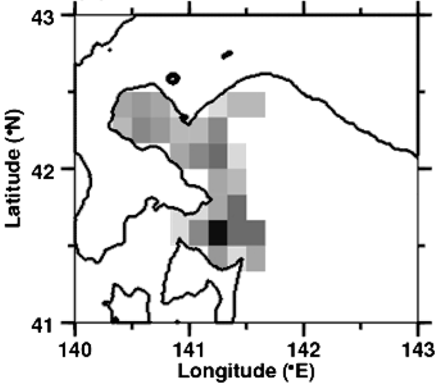


Figure 9. Horizontal distributions of the *SAI* (Spawning Area Index) values calculated by equation (3) for January (a), February (b) and March (c).

Discussion

Off the Pacific coast of Japan, adult walleye pollock migrate into the spawning area shallower than 200 m depth isobath in wintertime (Nakatani and Maeda, 1987). The quotient value with respect to the depth was also relatively high in areas shallower than 200 m. However, the spawning area of walleye pollock changes seasonally, and the quotient value with respect to water temperature decreased from 2°C. This suggests that adult walleye pollock have a spawning migration to avoid COW with the cold water less than 2°C. On the other hand, walleye pollock eggs spawned later in the season are adversely affected by variations in sea surface oceanographic conditions. The water mass which ST1 experience in sea surface changes from OW to COW in February to March (Fig. 6b), and the duration to hatch required 25 days or more in COW. COW sometimes becomes 0°C or colder. A rapid decrease in water temperature does not affect the hatching rate in the case of water temperatures higher than 0°C (Nakatani and Maeda, 1984). However, we can not rule out the possibility that the mortality rates may be affected by the occurrence of COW because larval fish were not sampled in water temperatures of less than 1°C (not shown).

Food production for larvae in Funka Bay is enhanced (Ohtani and Kido, 1980), and they remain in Funka Bay until the first summer (Kendall and Nakatani, 1992). Funka Bay is not only the most important spawning area but also a nursery ground of this stock. Kudo and Matsunaga (1999) showed that the timing of the bloom was strongly dependent on the inflow of OW or COW. Azumaya et al. (2001) showed that the spring diatom bloom occurring in Funka Bay corresponds to the timing when the net heat flux through the sea surface changes from cooling to heating. They suggested that vertical stability of the water column occurs due to the net heat flux rather than the intrusion of COW into Funka Bay which was regarded as the trigger of the spring bloom. Sakurai and Yamamoto (personal communications) found that larval fish avoided water less than 2.5°C in a laboratory culture experiment. Therefore it is suggested that the intrusion of COW with the cold water into Funka Bay does not give advantages of the survival and the food environment of larvae in Funka Bay.

Rosa et al. (2007) using ADCP and GEK data showed that in Hidaka Bay, an anti-clockwise flow of the Oyashio and the Coastal Oyashio occurs along the shelf slope from January to March. Kuroda et al. (2006) showed a seasonal current variation which has two current regimes; one a southeastward current from December to March and the other a northwestward current after April near the coast on the eastern shelf of Hidaka Bay. In the case that northwesterly winds occur, eggs which are spawned around the mouth of Funka Bay are transported into Funka Bay by wind-induced currents (Shimizu and Isoda, 1997). However, eggs which are distributed along the coast from Muroran to Tomakomai are probably transported away from the optimal larval nursery ground, from Funka Bay to Cape

Erimo by the southeastward coastal current. On the other hand, in the case that northwesterly winds become weak, eggs that are distributed along the coast from Muroran to Tomakomai are transported into Funka Bay by the Oyashio and the Coastal Oyashio. In this way, the currents on the eastern shelf of Hidaka Bay are dependent on the combined forcing of the wind stress and the Coastal Oyashio (Kuroda et al., 2006), so that the transportation of eggs and larvae into Funka Bay is affected by the change from the wind-induced currents to the Oyashio with OW and the Coastal Oyashio with COW. Hamatsu et al. (2004) reported that a decadal-scale change in the ocean environment around the main spawning area between the 1980s and the 1990s caused a change in the reproduction and recruitment of walleye pollock. Isoda et al. (1998) and Funamoto (2007) showed that years with a higher survival rate of larvae are notable for warm water and strong northwesterly winds during late winter. Consequently, it is suggested that the variation in the reproduction of walleye pollock is caused by wind-induced currents and the Oyashio with OW and the Coastal Oyashio with CO rather than the water masses of OW and COW.

Considering that the transportation into Funka Bay has the possibility of enhancing the survival of eggs, the initial position of particles, i.e., the spawning area is a very important factor in Euler-Lagrangian experiment in the model. The distribution of *SAI* estimated was similar to the distribution of ST1 (Fig. 3). Thus, this method is useful for determining not only the presumed spawning area of walleye pollock but also the initial position of a Euler-Lagrangian experiment in the model. In a more realistic model with Euler-Lagrangian experiment, it is necessary to include the variation of number and initial position of particles which are dependent on *SAI*.

In conclusion, the temperature at 10 m depth decreases from about 6.0°C in January to 2.0°C or colder in March due to the exchange of the water mass from TW to COW around Funka Bay. The spawning area of walleye pollock was mainly in OW and its location varies seasonally corresponding to the exchange of water masses. The duration to hatch of eggs in COW was longest of the five water masses. The proposed method to estimate the spawning area is useful for the prediction of the initial position of Euler-Lagrangian experiment in the model.

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北海道太平洋沿岸におけるスケトウダラの産卵場の水塊構造

矢部いつか[1]・日下　彰[2]・濱津友紀[3]・東屋知範[3†]・西村　明[4]

北海道太平洋沿岸における海洋物理環境（水温，塩分，水深）とスケトウダラの産卵場形成との関係を調べた．1月から3月にかけて，表層への沿岸親潮水の流入のため，噴火湾内外の海域（特に日高湾）において水温は低下した．Quotient分析から，スケトウダラの産卵場における平均水温，塩分はそれぞれ4.43°C，33.28で，水塊としては親潮水であった．スケトウダラの産卵場は苫小牧から津軽海峡口へ反時計回りに移動していた．卵が海面で経験する主な水塊は1·2月は親潮水，3月は沿岸親潮水であった．産卵から孵化までの時間は津軽暖流水で8日から20日，親潮水で15日から25日，沿岸親潮水で25日以上であった。これらのことから、水塊の相対的配置は産卵場形成や卵の発生速度に影響していると結論される．最後に，物理環境からスケトウダラの産卵場を推定する方法を提案した．

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[1] 日本NUS
[2] 中央水産研究所
[3] 北海道区水産研究所
[4] 西海区水産研究所
[†] azumaya@fra.affrc.go.jp