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VERTICAL DISTRIBUTION OF WALLEYE POLLOCK JUVENILES BEFORE AND AFTER THE PERIOD OF TRANSITION FOR FEEDING IN FUNKA BAY, HOKKAIDO, JAPAN

Yohei Kawauchi
Graduate School of Environmental Science, Hokkaido University, 3-1-1 Minato-cho, Hakodate, Hokkaido 041-8611, Japan., none_but_air@ees.hokudai.ac.jp

Osamu Shida
Central Fisheries Research Institute, Hokkaido Research Organization, 238 Hamanaka-cho, Yoichi-cho, Yoichi-gun, Hokkaido 046-8555, Japan.

Hiroya Okumura
Hakodate Fisheries Research Institute, Hokkaido Research Organization, 1-2-66 Yunokawa-cho, Hakodate, Hokkaido 042-0932, Japan.

Naoki Tojo
Akkeshi Marine Station, Aquatic Research Station, Field Science Center for Northern Biosphere, Hokkaido University, Aikappu, Akkeshi-cho, Akkeshigun, Hokkaido 088-1113, Japan.

Hiroki Yasuma
Field Science Center for the Northern Biosphere, Hokkaido University, 3-1-1 Minato-cho, Hakodate, Hokkaido 041-8611, Japan.

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Authors

Yohei Kawauchi, Osamu Shida, Hiroya Okumura, Naoki Tojo, Hiroki Yasuma, and Kazushi Miyashita

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Yohei Kawauchi*, Osamu Shida**, Hiroya Okumura***,

Naoki Tojo****, Hiroki Yasuma*****, and Kazushi Miyashita*****

Key words: walleye pollock, vertical distribution, acoustic survey, the period of transition for feeding.

ABSTRACT

We examined the vertical distributions of walleye pollock *Theragra chalcogramma* juveniles for two size groups (smaller and larger than 30 mm) during the period of transition for feeding (PTF) and after this period in Funka Bay, Hokkaido, Japan. Samplings were conducted in May and June in 2006 and 2007, and water temperature and salinity were measured. The correlation between juvenile sizes and distributed depth was observed using net sampling. From this result, size groups were divided by depth. In addition, the distribution and abundance of juveniles were examined using acoustic data. In the PTF (May), juvenile size increased with increasing depth, and after the PTF (June), most juveniles descended. In the PTF, juveniles smaller than 30 mm in TL dominated above 43 m depth in 2006, while juveniles larger than 30 mm in TL dominated below 18 m depth in 2007. After the PTF, juvenile sizes were larger in 2006 than in 2007. The relationships between juvenile distributions and water masses in the PTF were analyzed, and it was found that surface water of coastal Oyashio water (S-CO) dominated in the layers where small juveniles were distributed, and that Oyashio water (OW) dominated in the layers where large juveniles were distributed.

Paper submitted 03/31/10; revised 06/07/10; accepted 07/21/10. Author for correspondence: Yohei Kawauchi (e-mail: none_but_air@ees.hokudai.ac.jp).
*Graduate School of Environmental Science, Hokkaido University, 3-1-1 Minato-cho, Hakodate, Hokkaido 041-8611, Japan.
**Central Fisheries Research Institute, Hokkaido Research Organization, 238 Hamanaka-cho, Yoichi-cho, Yoichi-gun, Hokkaido 046-8555, Japan.
**Hakodate Fisheries Research Institute, Hokkaido Research Organization, 1-2-66 Yunokawa-cho, Hakodate, Hokkaido 042-0932, Japan.
****Akkeshi Marine Station, Aquatic Research Station, Field Science Center for Northern Biosphere, Hokkaido University, Aikappu, Akkeshi-cho, Akkeshi-gun, Hokkaido 088-1113, Japan.
*****Field Science Center for the Northern Biosphere, Hokkaido University, 3-1-1 Minato-cho, Hakodate, Hokkaido 041-8611, Japan.

I. INTRODUCTION

Walleye pollock *Theragra chalcogramma* is distributed in the North Pacific above the continental shelf and continental slope from the eastern coast of the Korean peninsula to the southern coast of California. Around Japan, this species is distributed from Hokkaido to Yamaguchi Prefecture in the Sea of Japan and to the Boso Peninsula in the Pacific [8]. In Hokkaido, a major fishing ground for this species in Japan, annual catches total about 200 thousand tons in weight [4].

The Japanese Pacific walleye pollock stock is distributed from the Pacific coast of Hokkaido to the Tohoku district. This is the most abundant stock around northern Japan [3]. To reveal the relation between the stock change of this economically and ecologically key species and the ocean environment is very important [15]. The population dynamics of this stock is directly affected by the change of recruitment each year. Moreover, early-life survival from the period of egg to recruitment impacts the interannual change of recruitment [12, 18].

The Japanese Pacific walleye pollock stock spawns mainly near the mouth of Funka Bay [7, 21], and most eggs are transported into the bay. Larvae and juvenile fish grow in the bay until the first summer [10, 11, 18] and then migrate to off the southeast Pacific coast of Hokkaido [5]. For this reason, Funka Bay is a very important nursery ground for the stock. The area around Funka Bay shows complicated water mass distributions due to the occurrence of cold, low-salinity Oyashio water, and warm, high-salinity Tsugaru Warm Current water, and these water mass distributions change seasonally and annually [14]. Changes in the physical environment influence the distributions of prey of walleye pollock and thus the stock size. Additionally, physical environments (e.g., water temperature) directly constrain the distribution of the pollock stock [6], and the seasonal or interannual change impacts the growth and survival.

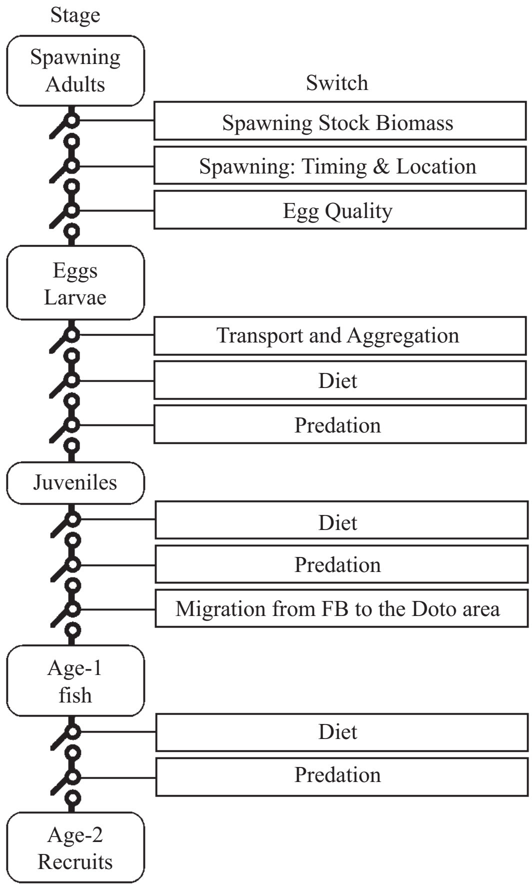

Fig. 1. Conceptual diagram of "Switch hypothesis" (Shida *et al.* 2007). Each "switch" is indicated the factor influenced to survival of walleye pollck *Theragra chalcogramma* at each growing stage.

Table 1. The number of net sampling, The number of CTD.

Year	Date	Net sampling	CTD
2006	May 10th-May 17th	6	41
	June 7th-June 14th	1	40
2007	May 9th-May 17th	8	40
	June 6th-June 14th	5	39

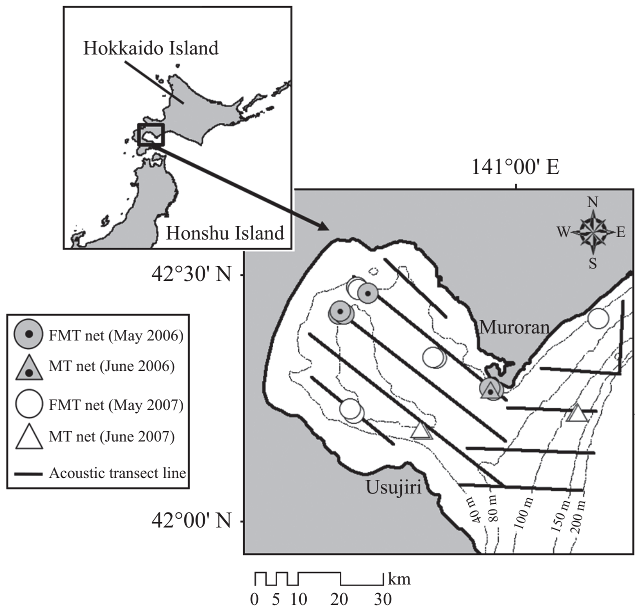

Fig. 2. Net sampling stations, Acoustic transect lines in Funka Bay.

Shida *et al.* [17] proposed a "switch hypothesis" that describes how the physical and biological environment impacts the growth and survival of walleye pollock from spawning to recruitment (Fig. 1). This hypothesis suggests that we have to reveal all processes from spawning to recruitment to understand the population dynamics of the stock. Around Funka Bay, there have been many studies of the processes from spawning by adult fish to the larval period [7, 10, 19], but few studies have focused on juveniles.

In Funka Bay, walleye pollock juveniles are thought to shift their diet to large-size prey as they grow to a threshold size (30 mm in TL), which is called the period of transition for feeding (PTF) [11, 12]. This was revealed by the composition of gastric contents [11]. However, the relation between juvenile distributions and environmental factors during the PTF and changes of the distributions after the PTF were not still verified very much. A better understanding of the environmental factors that influence the distribution of juveniles is needed because these factors in the PTF are one of the important "switches" for the growth processes of walleye pollock.

In this paper, the vertical distributions of walleye pollock juveniles of two size groups (smaller and larger than 30 mm) during and after the PTF are described using the net sample data and the acoustic data. We then compare the vertical physical environments from CTD data and interpret the juvenile distribution patterns.

II. MATERIAL AND METHOD

1. Materials

Surveys were conducted in Funka Bay in May and June 2006, and May and June 2007 by the R/V Kinsei maru (151 tons) (Table 1, Fig. 2). Net samples were collected of fish schools identified in acoustic data collected by a quantitative echosounder (Fig. 2, Table 2). In both years, we caught walleye pollock juveniles using a framed mid-water trawl net (FMT net, net mouth: 2 × 2 m, cod end mesh: 0.5 mm) in May and a mid-water trawl net (MT net, cod end mesh: 4 mm) in June. Sampled juveniles were measured for length and weight after being fixed in formalin or in ethanol. The size was measured as the total length (mm) in May because there was no difference between the fork length and the total length, and fork length (mm) was measured in June because juveniles grew up and the size grew. From compositions of samples sizes, May was identified as the PTF because many fish were

Table 2. The summery of net samplings in the survey area in May and June 2006 and 2007. FMT: framed mid-water trawl net, MT: mid-water trawl net.

Year	Trawl No.	Date	Start Position		End Position		Trawled depth (m)
			Latitude (N)	Longitude (E)	Latitude (N)	Longitude (E)	
2006	FMT 01	May 16th	42°28.43	140°34.85	42°28.27	140°35.48	20.0
	03		42°17.38	140°57.36	42°17.66	140°56.70	20.0
	04		42°17.58	140°56.64	42°16.77	140°58.11	33.0
	05		42°25.77	140°29.85	42°25.45	140°30.47	30.0
	06		42°25.86	140°29.93	42°26.24	140°29.37	68.0
	07		42°26.21	140°29.84	42°25.92	140°30.48	15.0
	MT 01	June 14th	42°17.42	140°57.32	42°17.69	140°56.81	36.0
2007	FMT 01	May 13th	42°13.83	140°32.88	42°14.27	140°23.21	30.0
	02		42°14.35	140°32.17	42°14.62	140°31.63	60.0
	03		42°28.91	140°32.81	42°29.18	140°32.32	30.0
	04		42°29.14	140°32.57	42°28.84	140°33.13	47.0
	05		42°28.94	140°32.81	42°29.28	140°32.23	69.0
	06		42°20.89	140°47.06	42°21.08	140°46.36	14.0
	07		42°21.01	140°46.42	42°20.65	140°46.96	30.0
	08		42°26.52	140°15.34	42°26.11	140°14.91	39.0
	MT 01	June 13th	42°15.10	140°12.30	42°15.09	140°11.26	41.0
	02		42°14.97	140°11.95	42°14.96	140°12.64	38.0
	03		42°14.93	140°12.34	42°14.93	140°12.06	101.0
	04		42°12.08	140°45.24	42°12.23	140°44.93	27.5
	05		42°12.20	140°44.76	42°11.78	140°45.16	43.5

collected that measured about 30 mm, and June was determined to be after the PTF because few samples smaller than 30 mm were collected (3 individuals in 585 samples).

Acoustic data were collected in the daytime (5:30-17:30) by an on-board quantitative echosounder EK60 (Simrad). Ship speed during the acoustic survey was 10 kts. We used echo data at 38kHz frequency to determine juvenile distribution s and to calculate the numbers of juveniles. In addition, all fish echoes in the echograms were assumed to be echoes from walleye pollock juveniles (> -70 dB) because > 95% by weight of the net collections was composed of juveniles.

CTD (Seabird) measurements were made a number of times in the area covering the acoustic transect lines (Table 1). Water temperature and salinity were measured at 1 m depth intervals.

2. The Relation between Juvenile Size and Depth

Walleye pollock juveniles descend from the surface layer to depth with growth [11, 16]. Therefore, we thought that the depth distribution of juveniles larger and smaller than 30 mm would differ. In May of both years, the relationship between juvenile size (TL) and depth (distributed depth of juveniles, Table 2) was analyzed using a simple liner regression analysis. From the regression formula, the depth where 30 mm juveniles were distributed (threshold depth) was calculated. In addition, the difference in size composition of juveniles collected above and below the threshold depth was verified using the Wilcoxon rank sum test.

In June of both years, when few net samplings were conducted, the depth dependency of juvenile sizes integrating samples of both years was verified with a simple liner regression analysis. In addition, the difference of juvenile sizes between 2006 and 2007 was analyzed with the Wilcoxon rank sum test. All analyses were performed using R ver. 2.10.1 (R Development Core Team 2009).

3. Vertical Distribution and Number of Walleye Pollock Juveniles

Echoes within 5 m from the sea surface and 2 m from the sea bottom were removed as acoustic dead zones, and volume backscattering strengths (Sv) of other echoes, which were assumed to be from pollock juveniles, were analyzed. The analytical resolution, corresponding to the integration grid of backscattering echoes, was 500 m in distance, and 1 m in depth (pulse duration: 1.024 ms). These processes were performed using Echoview ver. 4.7 (Myriax software Pty. Ltd.) for data collected in May and June.

From detected data, the number of individuals per 1 resolution N was calculated with the following formula:

$$N = (500 * 10^{Sv/10})/(10^{TS/10}) \quad (1)$$

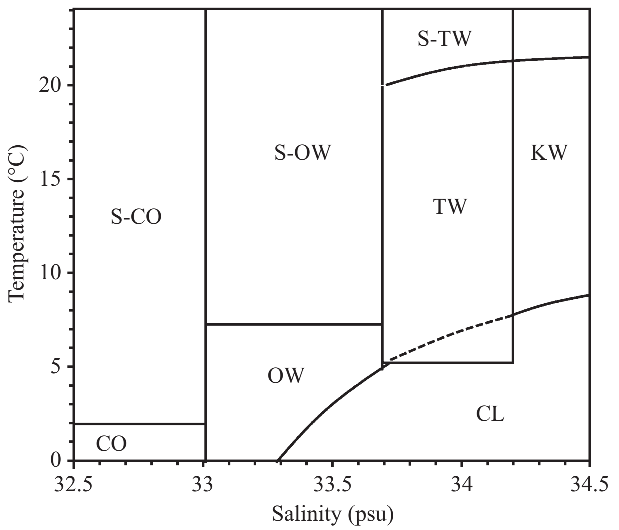

Fig. 3. The classification of water mass used in the present study (modified from Rosa *et al.* 2007). TW: Tsugaru warm current water, KW: Kuroshio water, OW: Oyashio water, CO: Coastal Oyashio water, CL: Cold lower-layer water, S-CO: Surface water of coastal Oyashio water, S-OW: surface water of Oyashio water, S-TW: Surface water of Tsugaru warm current water.

where Sv is the volume backscattering strength (dB), and TS is target strength (dB), which is backscattering strength in 1 individual of juvenile. The formula of Sadayasu [15] applicable to sizes from 50 mm to 100 mm was used to estimate the average theoretical TS. Sadayasu and Miyashita (unpublished) calculated the TS of four sizes of walleye pollock juveniles (20, 31, 40, 54 mm in the fork length) using the prolate spheroidal model [2] and found a strong correlation between juvenile size and the TS ($R^2 = 0.97$). This indicates that values of TS change linearly even for sizes smaller than 50 mm. From this, the following formula of Sadayasu [15] was used for juveniles both smaller and larger 50 mm in the present study:

$$TS = 26.57 \log L - 74.3 \qquad (2)$$

where L is the total length (May) or fork length (June) in cm. The number of individuals per 1 grid for the entire acoustic transect line was added horizontally, and the number of individuals at 1 m depth interval was calculated.

4. Vertical Physical Environments

Water temperature and salinity data in Funka Bay were averaged for each 1 m depth interval to observe vertical profiles of these environments. In addition, vertical structures of water masses were revealed using water temperature and salinity to classify water masses (Fig. 3) following Rosa *et al.* [14]. Comparing the vertical distributions of water masses and juvenile distributions, it was discussed how vertical physical environments impacted the vertical distributions of juveniles.

III. RESULT

Table 3. The number of individuals of juveniles collected in the layer above and below the threshold depth in May in each year: (a) May 2006 and (b) May 2007.

(a)

n = 519	< 43 m	> 43 m
< 30 mm	363 (80.5%)	27 (39.7%)
> 30 mm	88 (19.5%)	41 (60.3%)

(b)

n = 254	< 18 m	> 18 m
< 30 mm	18 (56.3%)	21 (9.5%)
> 30 mm	14 (43.7%)	201 (90.5%)

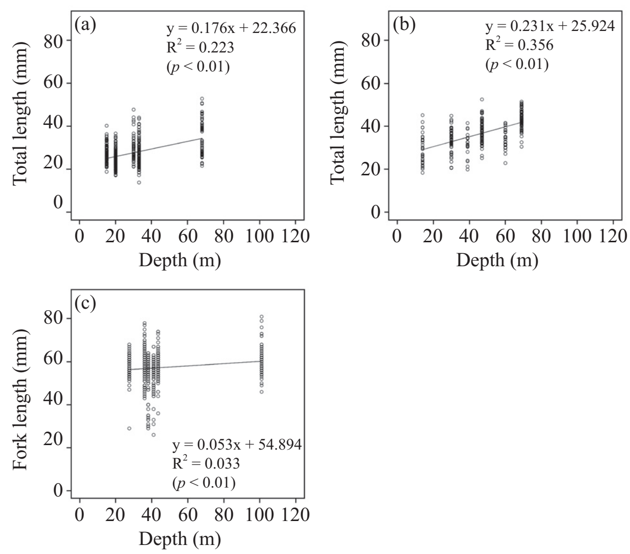

Fig. 4. The relation between juvenile size and depth. Horizontal axis shows depth (m), and vertical axis shows juvenile size (Total length (mm) in May, Fork length (mm) in June). Black line shows regression line: (a) May 2006 (n = 519), (b) May 2007 (n = 254), and (c): June (n = 585).

1. The Relation between Juvenile Size and Depth

Fig. 4 shows the relation between size and depth (Table 2) in May and June. The results of the regression analysis indicated a significant correlation between juvenile size and depth ($p < 0.01$). R^2 indicated correlations were not so strong (0.223 in May 2006 and 0.356 in May 2007) (Figs. 4(a) and (b)). The result suggests that depth could explain juvenile size in May partially (22.3-35.6%). In June, it was assumed the size could not be explained by depth because R^2 was 0.033, and the slope of the regression line was 0.053 (Fig. 4(c)). From these results, the threshold depth was calculated from regression formulas in May each year. It occurred near 43 m depth in May 2006 and 18 m depth in May 2007.

Table 3 shows the number of individuals caught and the ratio above and below the threshold depth in May each year.

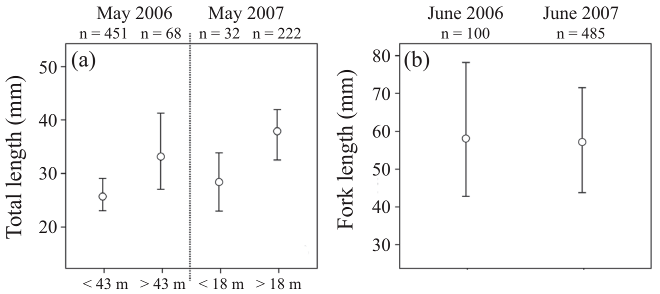

Fig. 5. The composition of juvenile sizes: (a) The composition of size in layers above and below the threshold depth in May and (b) The composition of sizes in June in each year. Horizontal axis shows layer that juveniles were caught, and vertical axis shows total length of juvenile. ○ in the figure shows median of juvenile size, and bar shows interquartile range (25-75%). The size in the layer below the threshold depth was larger than that above the threshold depth in both years ($p < 0.01$, Wilcoxon rank sum test). Additionally, the size in 2006 was larger than that in 2007 ($p < 0.05$, Wilcoxon rank sum test).

In May 2006, above 43 m, 363 samples smaller than 30 mm (80.5% in all samples above 43 m) were caught (Table 3(a)). In May 2007, below 18 m, 201 samples larger than 30 mm (90.5% in all samples below 18 m) were caught (Table 3(b)). In both years, juveniles of each size dominated over 80% in the layer where abundant juveniles were caught (n > 200), and juvenile sizes were divided by depth in these layers.

Fig. 5(a) shows the compositions of juvenile sizes above and below the each threshold depth. Juveniles below the threshold depth were larger than those above the depth in both years ($p < 0.01$). Fig. 5(b) shows compositions of juvenile sizes in June in both years. As described above, we assumed that juvenile size did not depend on depth. For this reason, comparing sizes of all samples between two year, sizes were larger in 2006 than in 2007 ($p < 0.05$).

2. Vertical Distribution and Number of Walleye Pollock Juveniles

Fig. 6 shows histograms of juvenile sizes above and below the threshold depth in May and June. It cannot be judged whether the histogram is normally distributed because few samples were collected below 43 m in May 2006 compared with those collected above 43 m (Fig. 6(a)). In a similar way, the normality of the histogram in May 2007 cannot be distinguished because the number of samples above 18 m was less than that below 18 m (Fig. 6(b)). In June, the number of samples greatly differed between the two years (Fig. 6(c)). For these reasons, the mean value was not used to calculate the average theoretical TS, and therefore, the median was used as the size parameter. Table 4(a) shows the median sizes of juveniles in each depth layer in May of each year, calculated from Fig. 5(a). Table 4(b) shows the median sizes in June of each year, calculated from Fig. 5(b). Substituting these medians into Eq. (2), target strength was calculated like the TS in Table 4.

Table 4. Target strength (TS, dB): (a) TS in May and (b) TS in June. "Median" in Fig. (a) shows values of medians of juvenile sizes in the period above and below the threshold depth calculated from net sampling data. "TS" in Fig. (a) shows target strength calculated to substitute these medians into Eq. (2). "Median" in Fig. (b) values of medians of juvenile sizes in all layer. "TS" in Fig. (b) shows target strength calculated to substitute these medians into Eq. (2).

(a)

	May.06		May.07	
	< 43 m	> 43 m	< 18 m	> 18 m
Median (mm)	25.50	33.05	28.20	37.75
TS (dB)	-63.23	-60.24	-62.07	-58.70

(b)

	Jun.06	Jun.07
Median (mm)	58.00	57.44
TS (dB)	-57.75	-53.86

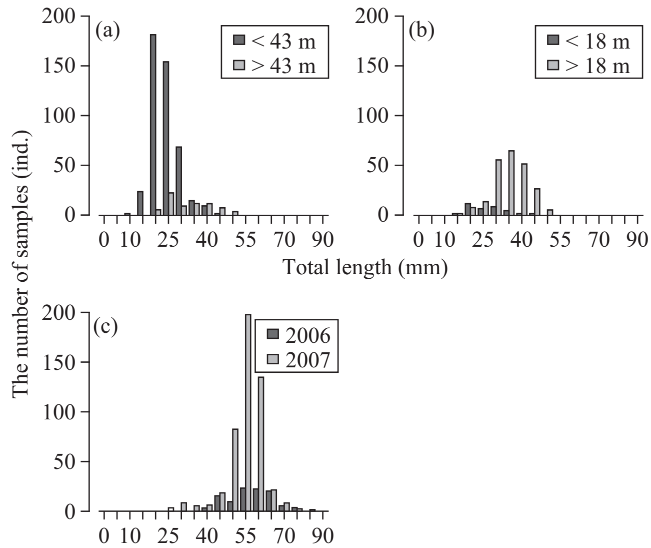

Fig. 6. Histograms of juvenile sizes above and below the threshold depth in May and June: (a) May 2006 (< 43 m: n = 451, > 43 m: n = 68), (b) May 2007 (< 18 m: n = 32, > 18 m: n = 222), and (c) June (2006: n = 100, 2007: n = 485). Horizontal axis shows juvenile size (May: total length in cm, June: fork length), and Vertical axis shows the number of samples.

The number of juveniles at each 1 m depth interval was calculated using the TS. Figs. 7(a), (b) show the vertical distributions of juveniles in May, and Figs. 7(c), (d) show the vertical distributions in June. In May, juvenile distribution was concentrated at 0-40 m in depth, and the number of individuals increased with decreasing depth in 2006 (Fig. 7(a)). In 2007, juveniles were abundant at 20-60 m depth (Fig. 7(b)). The dotted lines in Figs. 7(a), (b) show the threshold depths

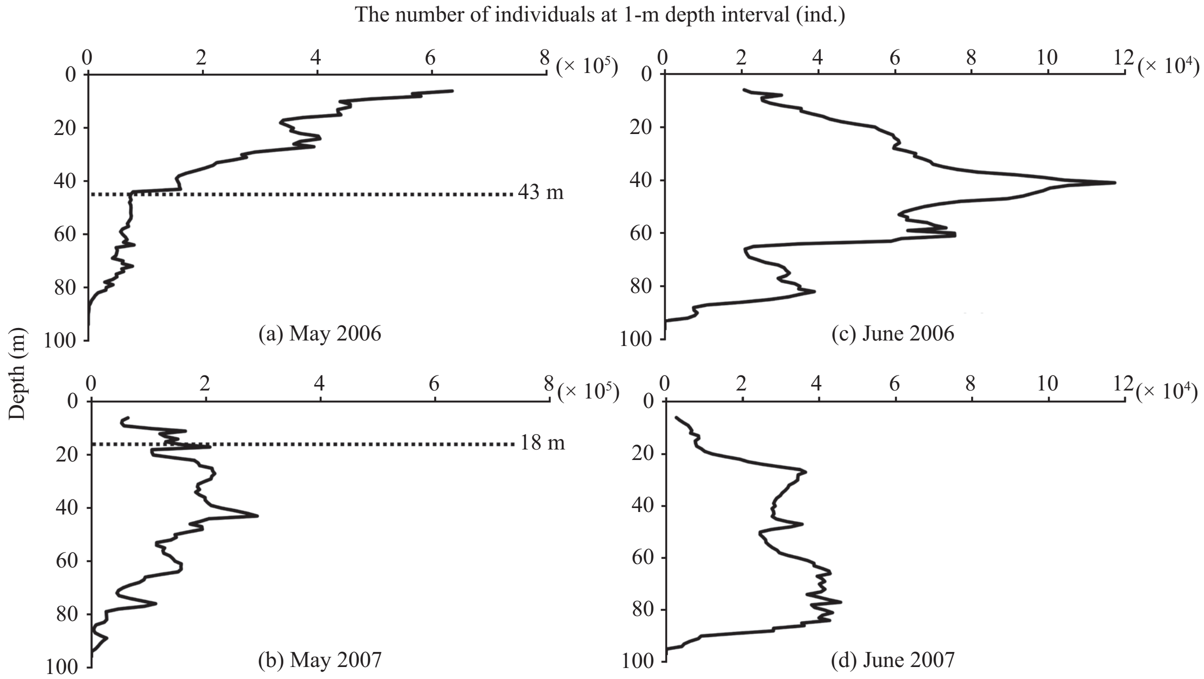

Fig. 7. Vertical profiles of distributions of walleye pollock juvenile. (a) and (b) The profile of the distribution in May in each year. (c) and (d) The profile in June in each year. Horizontal axis shows the number of individuals of juveniles at 1-m depth interval, and vertical axis shows depth (m). Dotted line in figures shows depth of threshold calculated from net sampling data.

calculated by regression formulas. As described above, sizes differed above and below the threshold depth, and larger juveniles occurred deeper. Juveniles smaller than 30 mm were distributed from the surface to the threshold depth in May 2006, and juveniles larger than 30 mm were distributed below the threshold depth in May 2007. Total number of individuals integrating the number at all depth layers was about 1.5×10^7 individuals in May 2006, and about 1.1×10^7 individuals in May 2007.

In June, the number of juveniles in 2006 peaked at 40 m depth (Fig. 7(c)), whereas in 2007, the peak was at 65-85 m depth (Fig. 7(d)). Compared with juvenile distributions in May, the center of the distributions shifted to deeper layer. Total number of individuals was about 4.4×10^6 individuals in June 2006 and about 2.4×10^6 individuals in June 2007. Additionally, the results of net sampling showed that juveniles were larger in 2006 than in 2007. This was the opposite result of May.

3. Vertical Physical Environments

Fig. 8 shows vertical profiles of water temperature and salinity in May and June in each year. Using the value of salinity considering water temperature in the classification of the water masses (Fig. 3) of Rosa *et al*. [14], the vertical structure of water masses was determined. In May 2006, surface water of the coastal Oyashio (S-CO), which was warm and of low-salinity, dominated at 0-40 m depth, and Oyashio water (OW), which was cold and of low-salinity, dominated below 40 m depth. Below 99 m depth, salinity exceeded 33.70 psu, and temperature rose to 5.7°C with depth. The water of this layer was estimated to be Cold lower-layer water (CL), because it was reported that the temperature of Tsugaru warm current water (TW) is 7°C or more at the inflow period of TW to Funka Bay or the surrounding area [13] (Fig. 8(a)). In May 2007, S-CO dominated at 0-20 m depth, which was shallower than in 2006, and The OW dominated below 20 m depth (Fig. 8(b)).

In June 2006, S-CO dominated at 0-46 m depth, and OW dominated below 46 m. CL existed below 98 m depth, which was the same as in May (Fig. 8(c)). In June 2007, S-CO dominated at 0-33 m depth, and OW dominated below 33 m depth (Fig. 8(d)). Additionally, the surface temperature (5 m depth) exceeded 10°C in both years (Figs. 8(c) and (d)).

IV. DISCUSSION

Our study revealed that juveniles during the PTF (May) increased in size with depth, and juveniles descended after the PTF (June). These results correspond to previous studies that show walleye pollock juveniles descend as they grow [11, 16]. It is said that physical environments that change with depth, and biological environments (species or distribution of prey) impacted the change of distributed depth of juveniles with growth [20].

The vertical distribution per size in May corresponded closely with the distributions of water masses. In May 2006, juveniles smaller than 30 mm were distributed in the high-temperature and low-salinity S-CO, which occurred at 0-40 m depth, and juveniles larger 30 mm were distributed in the low-

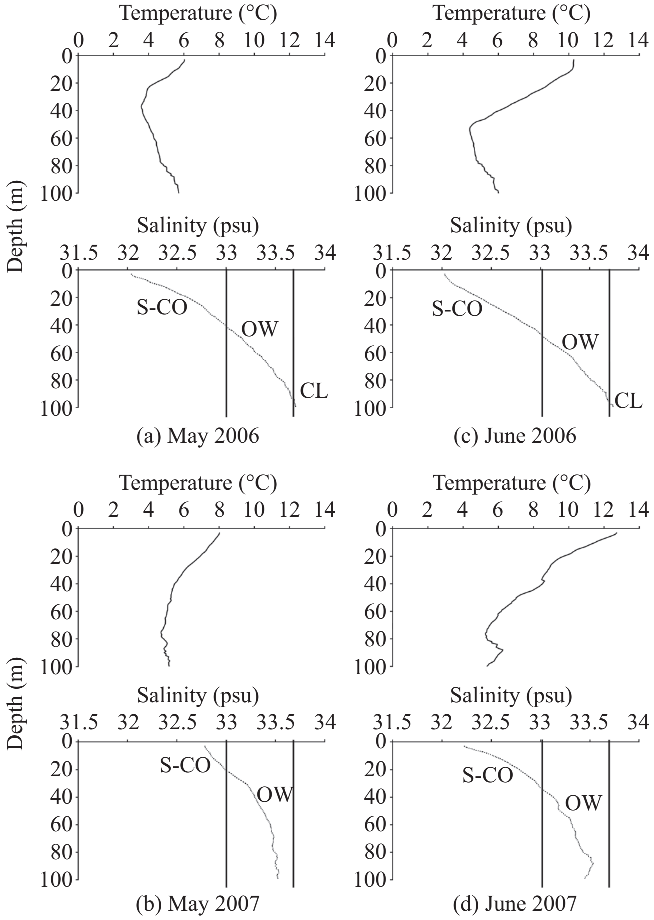

Fig. 8. Vertical profiles of water temperature and salinity. Water masses were separated by the value of salinity considering water temperature using Fig. 3. S-CO: surface water of coastal Oyashio water, OW: Oyashio water, CL: Cold lower-layer water.

temperature and low-salinity OW (Fig. 7(a) and Fig. 8(a)). In May 2007, small juveniles were abundant in the S-CO, and large juveniles were abundant in the OW as in 2006 (Fig. 7(b) and Fig. 8(b)). The difference of distributed water mass between two size groups probably impacts to the growth and the survival of juveniles directly or indirectly. It is thought that water temperature affects the metabolism of juveniles. In addition, it is possible that the species or the distribution of prey is different due to the difference of water mass. The copepod *Pseudocalanus minutus*, which is the main prey for walleye pollock juveniles smaller than 30 mm, is distributed in high density in the epipelagic zone, where surface water of the Oyashio system occurs, from March to April [11], while the larger copepod *Neocalanus plumchrus*, which is the main prey for juveniles larger than 30 mm, is abundant high at intermediate depths and near the bottom (3-6°C) in June [9, 11]. From here onwards, it is indicated that prey select different environments between species. In the present study, S-CO dominated in the epipelagic zone, and OW dominated below the layer in both years. The differences in species of prey may have been due to differences in water masses, and impact juvenile distributions per size indirectly. In the future, it is a necessity to reveal the species of prey per water mass, and to verify that juveniles of two size groups fed what kind of prey.

As described above, the center of juvenile distribution descended in June. Ohtani [13] reported that the epipelagic zone in Funka Bay increases in temperature from June to July. Additionally, Nakatani and Maeda [11] reported an alteration of water mass in June, when the surface temperature exceeded 10°C. As a result, the maximum layer of chlorophyll declines [1], and *P. minutus* disappears from the epipelagic zone in Funka Bay [11]. In the present study, surface temperature in June in both years exceeded 10°C (Figs. 8(b) and (d)). From this result, it is thought that water of epipelagic zone metamorphosed in the period of our survey. In this way, it is likely that prey in the epipelagic zone decreased in abundance and that juveniles larger than 30 mm in June migrated deeper to feed on larger prey.

The ratio of juvenile size in each layer in the PTF differed in the two years. Juveniles smaller than 30 mm were abundant above the threshold depth in May 2006, and those larger than 30 mm were abundant below the threshold depth in May 2007. Additionally, after the PTF, juveniles were larger in 2006 than in 2007. This was the opposite result of May. It is possible that juveniles are affected by different physical environments or by different prey environments from year to year. In the future, we need to verify the biological factors that affect to juvenile distributions of two size groups by analyzing the composition of gastric contents of juveniles in the period of our survey.

In the present study, the threshold depth in May was calculated from the regression line using data of the net samplings. The TS of sizes smaller than 30 mm was applied to juveniles distributed shallower than the threshold depth, and the TS of sizes larger than 30 mm was applied to juveniles in deeper layers (Table 4). The abundance of juveniles along the acoustic transect lines was calculated from acoustic data, and the vertical profiles were made (Figs. 7(a) and (b)). However, the vertical variation of abundance of juveniles may have been over- or underestimated because the size composition of juveniles was classified into only two categories. In the future, it will be necessary to divide the size categories into more groups. As a result, it is thought that the detailed vertical size variation of juveniles can be known, and the more accurate distribution tendency and the abundance can be calculated.

Values of R^2 were 0.223 in May 2006 and 0.356 in May 2007 (Figs. 4(a) and (b)), meaning that depth can explain from 22.3 to 35.6% of the change in size, which suggests that other explanatory variables to the size probably exist besides depth. The species or the distribution of the prey, which might be influenced by the physical environment as described above, or the current around Funka Bay that influenced the passive migration of juveniles are thought as the main valuables. It will be necessary to clarify these factors to decide the distribution of juveniles by observing the spatial correspondence between the distribution and these factors, or by using statistical models in the future.

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