Spatial and Temporal Distribution of Pacific Cod *Gadus macrocephalus* Juveniles in Mutsu Bay, Japan

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The spatial distributions of Pacific cod (*Gadus macrocephalus*) juveniles and their food organisms were examined in Mutsu Bay from April to July during 1988–1997. In April, large larvae (≤25 mm in total length (TL)) and pelagic juveniles (>25 mm TL) were widely distributed in the bay, and were concentrated at the same depths as calanoid copepodites during daylight hours. Geographical changes in cod TLs might have been due to transport by the Tsugaru Warm Current. After mid- and late May, juveniles and calanoid copepodites occurred on the bottom. Mean densities of cod juveniles fluctuated annually in April and June, and high densities occurred when calanoid copepods were abundant. Juveniles were rarely found at temperatures >12°C, and it is likely that they migrate out of the bay after late June when temperatures increase and the abundance of prey decrease in the bay. Pacific cod use Mutsu Bay as a nursery ground, and calanoid copepodites sustain cod larvae and juveniles as their prey until mid-June. Large fluctuation in mortality of Pacific cod might occur in pelagic juvenile and subsequent stages after April in Mutsu Bay.

Key words: Pacific cod, juvenile, spatial distribution, nursery ground, Copepoda, Mutsu Bay, Tsugaru Warm Current, mortality

Introduction

The match-mismatch hypothesis (Cushing and Dickson, 1976, Cushing, 1990) has been used to explain recruitment variability in fishes by many researchers, and has recently changed to a growth-predation hypothesis. Predation may be a potent regulator of year-class strength (Hunter, 1981) and potentially more important than starvation as a regulator of recruitment (Houde, 1987). Larvae that hatched at a large size have a greater flexibility in their first feeding time, and the risk of predation is size dependent (Miller *et al.*, 1988). Survival is a direct function of growth, mediated through size-dependent predation (Anderson, 1988). Cumulative mortality based on interannual variations in the growth rate in late larval and pelagic juvenile stages of Atlantic cod (*Gadus morhua*) is an important factor affecting subsequent year-class strength (Campana, 1996). Fast growth of Atlantic cod larvae increases the survivorship, and selection for fast growth is stronger in a slow growing cohort (Meekan and Fortier, 1996). The survival of Atlantic cod has been investigated in detail, but the early life history of Pacific cod (*Gadus macrocephalus*) remains largely unknown.

Mutsu Bay is one of the spawning grounds of Pacific cod in Japan. From early December to mid-February, adult cod migrate into the bay from the open sea and spawn in the inner parts of the bay (Kawamura and Kokubo, 1950). However in recent years, spawning has occurred mainly at the bay mouth, judging from the distribution of small larvae (Takatsu *et al.*, unpublished). Larvae ascend in the water column after hatching from demersal eggs and are transported by the Tsugaru Warm Current (TWC; Ohtani and Terao, 1974) to the inner part of the bay where larval prey (nauplii and copepodites) are abundant. The prey items for juveniles (26–70 mm in total length (TL)) are calanoid copepodites from April to June, and gammarid amphipods and fish (>70 mm TL) in July (Takatsu *et al.*, 1995). The vertical distribution of pelagic juveniles in the eastern Pacific has been documented (Boehlert *et al.*, 1985), but there is no information on the spatial distribution of juveniles in Mutsu Bay. To understand survival mechanisms in the field, the interannual fluctuations in abundance during the early life stages must be clarified, especially in the juvenile stage. In the present study, we studied the vertical and horizontal distributions of Pacific cod juveniles and their prey, and examined interannual fluctuations in the density of pelagic and demersal juveniles in Mutsu Bay.

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Table 1. Number of sampling stations and samples in Mutsu Bay. Data of plankton nets in 1990 were quoted from Takatsu *et al.* (1992).

Dates	Sampling Gear	Target	Number of sampling stations	Number of samples
7–9 Apr. 1991	Beam Trawl Horizontal	Pacific cod larvae and juveniles	6	10
9 Apr. 1991	MTD nets Horizontal	Calanoids	1	3
9–11 Apr. 1991	Beam Trawl Horizontal	Pacific cod larvae and juveniles	14	14
	NORAPC net Vertical	Calanoids	22	22
12–15 Apr. 1993	Beam Trawl Horizontal	Pacific cod larvae and juveniles	8	12
	NORAPC net Vertical	Calanoids	16	16
14–16 Apr. 1992	Beam Trawl Horizontal	Pacific cod larvae and juveniles	12	16
15–16 Apr. 1992	MTD nets Horizontal	Calanoids	2	6
18–20 Apr. 1994	Beam Trawl Oblique	Pacific cod larvae and juveniles	13	13
	NORAPC net Vertical	Calanoids	18	18
21–22 Apr. 1997	Beam Trawl Oblique	Pacific cod larvae and juveniles	5	5
	NORAPC net Vertical	Calanoids	9	9
22–24 Apr. 1996	Beam Trawl Oblique	Pacific cod larvae and juveniles	10	10
	NORAPC net Vertical	Calanoids	15	15
24–27 Apr. 1990	Beam Trawl Horizontal	Pacific cod larvae and juveniles	11	17
	NORAPC net Vertical	Calanoids	23	23
25–26 Apr. 1990	MTD nets Horizontal	Calanoids	3	9
26–28 Apr. 1995	Beam Trawl Oblique	Pacific cod larvae and juveniles	10	10
	NORAPC net Vertical	Calanoids	17	17
18–23 May 1989	Otter Trawl net (mid-water)	Pacific cod juveniles	5	6
	Otter Trawl net (bottom)	Pacific cod juveniles	13	13
3–6 June 1997	Otter Trawl net (bottom)	Pacific cod juveniles	7	7
	NORAPC net Vertical	Calanoids	24	24
4–6 June 1996	Otter Trawl net (bottom)	Pacific cod juveniles	6	6
	NORAPC net Vertical	Calanoids	21	21
7–8 June 1995	Otter Trawl net (bottom)	Pacific cod juveniles	6	6
	NORAPC net Vertical	Calanoids	16	16
11–14 June 1991	Otter Trawl net (bottom)	Pacific cod juveniles	5	5
	NORAPC net Vertical	Calanoids	28	28
13–14 June 1990	Otter Trawl net (bottom)	Pacific cod juveniles	5	5
	NORAPC net Vertical	Calanoids	16	16
22–24 June 1993	Otter Trawl net (bottom)	Pacific cod juveniles	6	6
	MTD nets Horizontal	Calanoids	3	9
	NORAPC net Vertical	Calanoids	22	22
28–30 June 1994	Otter Trawl net (bottom)	Pacific cod juveniles	7	7
	NORAPC net Vertical	Calanoids	24	24
12–18 July 1988	Smith–McIntyre grab	Gammarid amphipods	22	66
18–22 July 1989	Otter Trawl net (mid-water)	Pacific cod juveniles	4	4
	Otter Trawl net (bottom)	Pacific cod juveniles	11	11

Materials and Methods

Field sampling

Samplings were conducted in Mutsu Bay by the R/V *Ushio-maru* (107.85 tons in 1988–1992 and 128 tons in 1993–1997) and T/S *Oshoro-maru* (1,383 tons) from April to July in 1988–1997 (Table 1). In 1990–1997, samplings were carried out in April and June, except for June 1992, when the R/V *Ushio-maru* was being rebuilt. Mutsu Bay was divided into four regions: bay mouth, northern part of West Bay, southern part of West Bay, and East Bay (Fig. 1); the later three regions were treated as the inner part of the bay. In April, larval and juvenile Pacific cod were collected with a non-closing beam trawl net (2.0 m×2.5 m mouth; Maeda *et al.*, 1979; Nakatani, 1987). This net was composed of three sections of reducing mesh size from the net opening to the codend (13 mm–3.1 mm–0.33 mm in 1990 and 13 mm–3.1 mm–0.72 mm in 1991–1997). The net mouth area was 0.90 m^2 for the 3.1 mm mesh, and 0.16 m^2 for the 0.33 mm and 0.72 mm meshes. Horizontal tows of beam trawl net were carried out in April 1990–1993, and oblique tows were carried out in 1994–1997 instead of horizontal tows. Horizontal tows were carried out at the objective depth layers for 10–15 min at approximately 1.5 $m \cdot s^{-1}$ of net speed. At nine stations (Stn. 13, 19 and 31 in 1990; Stn. 16′ and 32 in 1991; Stn. 19 and 43 in 1992; Stn. 31 and 43 in 1993; Fig. 1), cod larvae and juveniles were collected at three different depths to clarify their vertical distribution. Oblique tows were carried out from 2 m above the sea bottom to the surface at approximately 1.5 $m \cdot s^{-1}$. The sampling depth was monitored by a bathymeter. From May to July in 1989–1991 and 1993–1997, cod juveniles were collected with a small otter trawl net (4.4 m×5.9 m mouth, 90 mm mesh and 12 mm cod-end mesh; Maeda *et al.*, 1979; Nakatani, 1987) in midwater and on the bottom (Table 1). This otter trawl net was towed for 10–15 min at approximately 1.5 $m \cdot s^{-1}$ at the objective depth layers, and the sampling depth was

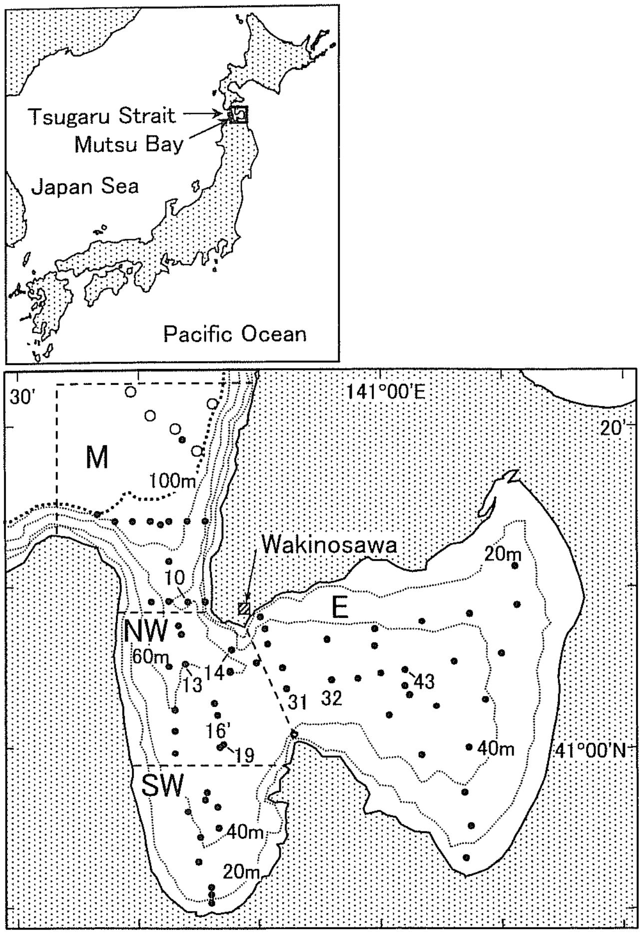

Figure 1. Location of Mutsu Bay (upper) and contours of depth and locations of sampling stations (lower). Solid circles and numerals show the locations of sampling stations and station numbers by T/S *Oshoro-maru* and R/V *Ushio-maru*. Open circles show the locations of sampling stations by R/V *Seiho-maru* of Aomori Prefectural Fisheries Experimental Station. Mutsu Bay was divided into four regions, M: bay mouth; NW: northern part of West Bay; SW: southern part of West Bay; and E: East Bay.

monitored by a bathymeter. On board, cod larvae and juveniles were immediately fixed in a 5–10% buffered formalin solution in seawater for 24–36 hours, and then transferred into a 70% ethanol solution. Fixation causes cod juveniles to shrink about 5% in size (Yoshida *et al.*, unpublished), but this shrinkage was not considered in this study.

To clarify the vertical distribution of Pacific cod larvae and juveniles, calanoid copepods were obtained by horizontal tows with three MTD nets (0.56 m diameter and 0.33 mm mesh; Motoda, 1971) equipped with flowmeters in April 1990–1992 and June 1993 (Table 1). MTD tows were carried out at six stations in April (Stn. 10, 19 and 31 in 1990; Stn. 16′ in 1991; Stn. 19 and 43 in 1992; Fig. 1) and three stations in June (Stn. 13, 30 and 43). To compare interannual variations in the abundance of calanoid copepodites, vertical hauls were carried out from the sea bottom to the surface with a NORPAC net (0.45 m diameter, 1.8 m length and 0.33 mm mesh) in April and June 1990 (Takatsu *et al.*, 1992), 1991 and 1993–1997 (Table 1). Zooplankton samples were immediately fixed in a 5% buffered formalin solution in seawater. A Smith-McIntyre grab was used for gammarid-amphipod sampling during 12–18 July 1988 (Table 1). Sediment was collected three times using the grab at each of the 22 predetermined stations, washed in a 1.0 mm mesh sieve, and immediately fixed in a 10% buffered formalin solution in seawater. Water temperatures and salinities were measured with a VARIOSENS III (Impulsphysic), CTDs (Neil Brown and Sea Bird Electronics) and a DBT (MetOcean, temperature only). In addition, surface water samples were collected in April 1990-1997, June 1990–1991 and June 1993–1997. Salinities were measured with a salino-meter.

Laboratory analyses

Cod larvae and juveniles were counted and measured for total length to the nearest 0.1 mm with an electric slide caliper. Cod >25 mm TL (>22 mm in standard length) were classified as juveniles (Takatsu *et al.*, 1995). Copepodites from net samples and gammarid amphipods from the grab were identified to the lowest practical taxa and counted.

Data analysis

The number of individuals per 1,000 m^3 was used for the density for Pacific cod larvae and juveniles collected in April. The filtered volume of the beam trawl net was calculated from its effective mouth area and the towing distance integrated by the electromagnetic log. The effective mouth area of the beam trawl net was 0.90 m^2 (3.1 mm mesh), because 90% of cod reached 3.1 mm in body depth (about 19 mm TL) in April. Towing distance of the beam trawl net under 8 m depth was used to estimate each filtered volume, because larvae were found under this depth in March (Takatsu *et al.*, unpublished).

Because juveniles were concentrated on the bottom in May–July (see below), the density (number of individuals per 1,000 m^2) at each sampling station was calculated from mouth width of the otter trawl net (5.9 m) and the towing distance on the bottom. It was assumed that the filtration efficiency of each trawl net for cod was 100%.

A one-way ANOVA was used to compare of mean TLs among three or more samples. If variances were determined to be heteroscedastic by F_{max}-test, the TLs were log transformed. If variances of the log-transformed TLs were determined to be heteroscedastic by F_{max}-test, the Kruskal-Wallis test was used to compare median TLs. Spearman's rank correlation coefficient was estimated between the mean densities of cod in April and in June. Significance levels were set at 0.05.

Commercial landings of Pacific cod at Wakinosawa Village (Fig. 1) from the 1989 fishing period (November 1989-March 1990) to the 1996 fishing period (Aomori Prefectural Aquaculture Research Center, unpublished) were used as an abundance index of spawners. Variation of fishing effort around Wakinosawa Village was small during these fishing periods.

Results

Spatial distribution of larval and juvenile Pacific cod and vertical distribution of calanoid copepods in April

From April to June, the main food organisms of cod juveniles are calanoid copepods (Takatsu *et al.*, 1995). In April 1990-1992, relatively high cod densities occurred at depths where calanoids were abundant during daylight hours (Figs. 2–3). The vertical distribution of cod was investigated at Stn. 13 instead of Stn. 10 in late April 1990, because commercial bottom set-nets for demersal fishes were positioned near Stn. 10, making it dangerous to tow the beam trawl net near the bottom.

Although larvae and pelagic juveniles of cod were widely distributed in the bay, densities were low at the bay mouth in April 1990–1992 (Fig. 2A, B, C). Only two larvae were collected in East Bay in April 1993 (Fig. 2D, Table 2). Median temperatures at 15 m depth in the bay in 1991 and 1996 were lower (6.0°C and 6.4°C, respectively) than in other years (7.2–9.0°C, in 1990, 1992–1995 and 1997). The median salinity at the surface in 1991 was lower (32.44 PSU) than in other years (33.08–33.76 PSU, in 1990 and 1992–1997).

Mean TLs did not differ significantly among depths at six of the seven stations in April (one-way ANOVA, Stn. 19 in 1992; $P=0.015$, but others; all $P>0.17$). Mean TLs differed significantly among stations in 1990–1992 (one-way ANOVA, all $P<0.001$). Larvae and small juveniles were collected in West Bay and at the bay mouth, whereas large juveniles were collected in East Bay. For example, in April 1991, the minimum-mean-maximum TLs were 5.1–11.7–18.6 mm in the bay mouth ($N=4$), 11.7–24.4–32.1 mm in northern and southern West Bay ($N=96$) and 11.7–26.5–36.1 mm in East Bay ($N=231$).

Spatial distribution of Pacific cod juveniles from May to July and vertical distribution of calanoid copepods in June

Cod juveniles were chiefly distributed on the bottom (97.7%), and the remaining individuals (2.3%) were collected in midwater at five stations in May 1989. No pelagic juveniles were collected at four stations in July 1989. Calanoid copepods were concentrated near the bottom at three stations in the inner part of Mutsu Bay during daylight hours in June 1993 (Fig. 3).

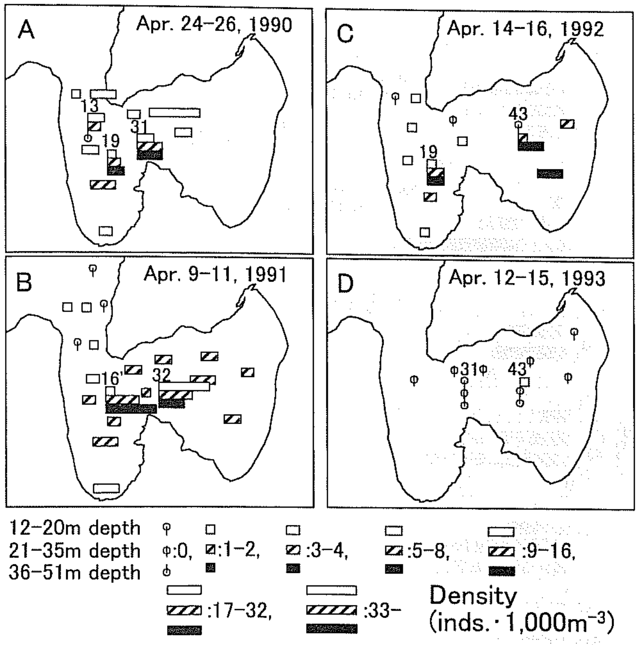

Figure 2. Spatial distribution of Pacific cod larvae and pelagic juveniles collected by horizontal tows by a beam trawl net in April 1990–1993. The densities of each towing depth were grouped into three strata. Each numeral shows station number with bars.

Table 2. Mean and range of total length and number of individuals of Pacific cod from 1989 to 1997.

	Number of individuals sampled		Total length (mm)	
Sampling dates	Larvae	Juveniles	Mean	Range
9–11 Apr. 1991	117	214	25.7	5.1 – 36.1
12–15 Apr. 1993	2	–	19.5	17.5 – 21.4
14–16 Apr. 1992	15	50	31.3	13.0 – 46.3
18–20 Apr. 1994	1	–	14.9	
21–22 Apr. 1997	2	3	25.9	21.4 – 30.4
22–24 Apr. 1996	6	2	19.4	12.6 – 32.0
24–27 Apr. 1990	3	167	37.9	20.9 – 56.7
26–28 Apr. 1995	21	52	31.3	10.1 – 44.1
18–23 May 1989	–	1,099	59.3	37.0 – 107.6
3–6 June 1997	–	1,135	62.8	37.0 – 90.2
4–6 June 1996	–	902	54.1	36.4 – 86.1
7–8 June 1995	–	420	67.8	41.4 – 94.8
11–14 June 1991	–	525	69.4	51.7 – 87.4
13–14 June 1990	–	161	69.1	43.0 – 84.4
22–24 June 1993	–	250	64.9	52.3 – 86.1
28–30 June 1994	–	227	70.9	49.9 – 106.6
18–22 July 1989	–	139	103.2	73.8 – 174.0

Areas where cod juveniles were dense from May to July varied annually (Fig. 4). Highest densities of juveniles were observed in East Bay from May to early June (in May 1989, June 1995, June 1996 and June 1997), and in the northern part of West Bay and bay mouth from late June to July (in July 1989, June 1993 and June 1994). In mid-June,

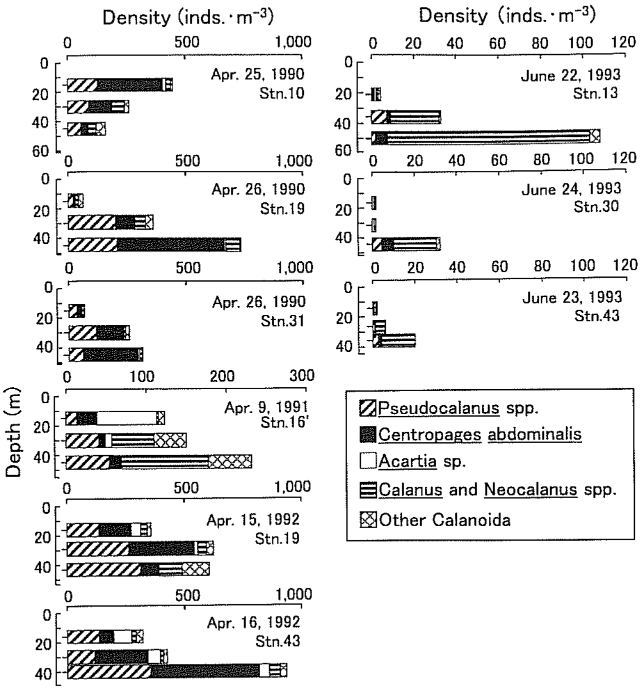

Figure 3. Vertical distribution of calanoid copepods collected by horizontal tows with three MTD nets in April and June. Data in April 1990 was quoted from Takatsu *et al.*, (1992).

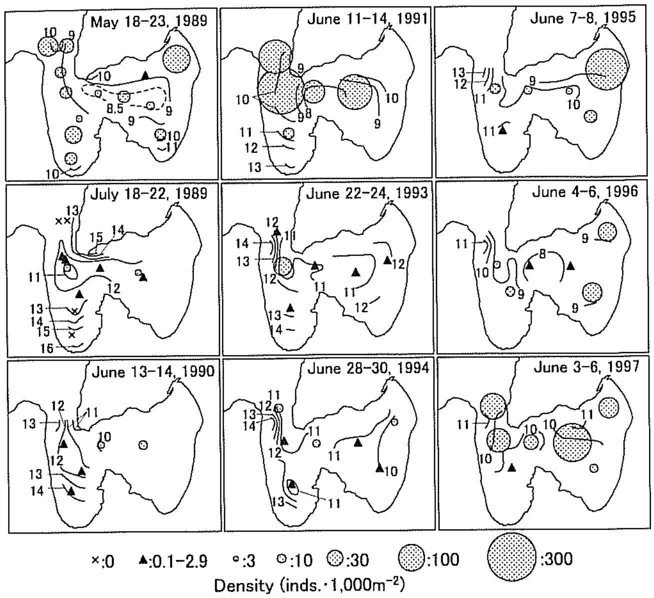

Figure 4. Horizontal distribution of Pacific cod juveniles collected by horizontal tows with an otter trawl net on the bottom from May to July 1989–1997. Contours show water temperatures on the bottom (solid lines, °C).

the highest densities occurred in East Bay in 1990 (Stn. 43; 9.2 inds.·1,000 m^{-2}), but in the northern part of West Bay (Stn. 13; 282 inds.·1,000 m^{-2}) in 1991. In May 1989 and June 1996, a few juveniles were distributed in central Mutsu Bay, where water temperatures on the bottom were low. In contrast, most juveniles were concentrated where temperatures were <12°C in July 1989. Median TLs of cod were significantly different among sampling stations from May to July during 1989-1997 (Kruskal-Wallis test, all P<0.004). Small and large juveniles were chiefly found in West Bay and at the bay mouth, and middle-sized juveniles were distributed in East Bay on five of nine occasions. However, there was no consistent tendency in fish size among stations on the remaining four occasions. In mid-June 1991 and early June 1996, water temperatures on the sea bottom were lower (about −1.5°C to −2.0°C) than in other years (Fig. 4). Similarly, lower water temperatures in the bay from February to June in 1991 and 1996 were recorded (Aomori Prefectural Aquaculture Research Center, 1992–1999). Median salinity at the surface in East Bay was lower in June 1991 (32.59 PSU) than in other years (32.81–33.40 PSU, in 1990 and 1993–1997).

Horizontal distribution of gammarid amphipods in July 1988

Gammarid amphipods are one of the primary prey of cod in July (Takatsu *et al.*, 1995) and were mainly distributed at

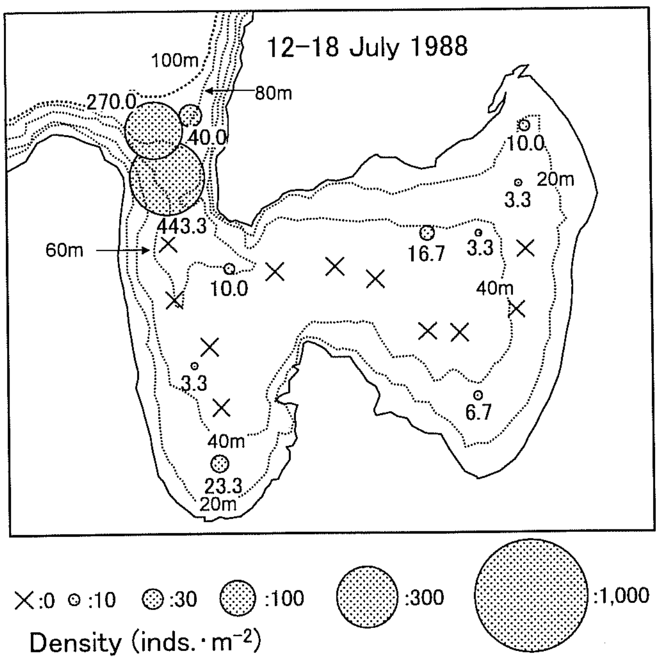

Figure 5. Horizontal distribution of gammarid amphipods on the bottom collected three times using the Smith-McIntyre grab (covering 0.10 m^2) during 12–18 July 1988.

the bay mouth in July 1988 (Fig. 5, 40.0–443.3 inds.·m^{-2}). A few gammarids were found at shallow stations (<42 m depth, 0–23.3 inds.·m^{-2}), and none were collected at 43–65 m depth, except at Stn. 14 (64 m depth, 10.0 inds.·m^{-2}).

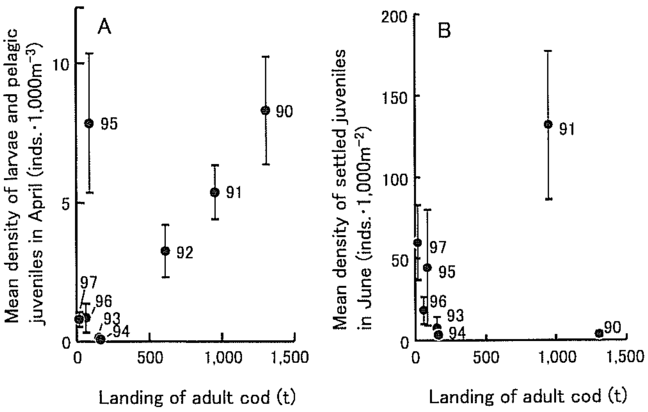

Figure 6. Relation between commercial landings (metric tons) of Pacific cod at Wakinosawa Village (Aomori Prefectural Aquaculture Research Center, unpublished) as the abundance index of adult spawners and mean densities (±standard error) of cod larvae and juveniles in April (A) and in June (B). Each numeral shows the year-class.

Interannual fluctuations in density of Pacific cod in April and June 1990–1997

A positive correlation was found between commercial landings of Pacific cod as an abundance index of adult spawners, and mean densities of cod larvae and juveniles in April on seven of eight occasions (Fig. 6A). The 1995 year-class had a high mean density in spite of the low catch of spawners. No eradicated year-class (low density in April despite high catch of spawners) was found. There was no correlation between landings of spawners and mean densities of juveniles in June (Fig. 6B). The highest mean density in June was recorded in 1991 (132 inds.$\cdot$1,000 m^{-2}). In 1990, the mean density in April was the highest (8.3inds.$\cdot$1,000 m^{-3}), but that in June was the sixth highest among seven years (3.6 inds.$\cdot$1,000 m^{-2}). The 1995 year-class showed high mean density in April, but a lower density was recorded in June than in the 1991 and 1997 year-classes. No significant correlation was found between the mean densities in April and June among the seven years (Spearman's rank correlation coefficient: r_s=0.29, P>0.05).

Abundance of calanoid copepods in April and June 1990, 1991 and 1993-1997

In April, relatively high mean abundances of calanoids were recorded in 1993, 1995 and 1996 ($6.6\cdot10^4$ inds.$\cdot$m^{-2}, $8.0\cdot10^4$ inds.$\cdot$m^{-2} and $9.8\cdot10^4$ inds.$\cdot$m^{-2}, respectively, Fig. 7). In 1991, the mean abundance of calanoids in June ($1.7\cdot10^4$ inds.$\cdot$m^{-2}) was higher than in April ($1.1\cdot10^4$ inds.$\cdot$m^{-2}), but there was an opposite trend in other years.

Discussion

Relatively high cod densities occurred at layers where calanoids were abundant during daylight hours in April 1990–1992 (Figs. 2–3). Temperatures >12°C were not suitable for cod (discussed below) and were not found at any depths in April. Cod larvae and pelagic juveniles might feed on calanoid copepods, and a geographical change in the vertical distribution of cod might be influenced by the distribution of calanoid copepods (Fig. 8A). An ontogenetic shift of cod toward deeper strata may not be a determinant, because significant differences in cod size rarely occurred among depths. The geographical change in cod TLs in April might have been due to transport by the Tsugaru Warm Current (TWC; Ohtani and Terao, 1974). Cod spawn mainly at the bay mouth from late December to late February (Takatsu *et al.*, unpublished). Currents generally flow counterclockwise in the bay (Ohtani and Nakamura, 1985). This explains why large juveniles were found in East Bay, but larvae and small juveniles occurred in West Bay and at the bay mouth in April.

Cod juveniles chiefly occurred on the bottom after May, and calanoid copepods were concentrated near the bottom in June (Figs. 3, 8B). Many juveniles occurred in shallow areas in mid- and late May 1989 and early June 1996 (Fig. 4). Calanoids, especially *Centropages abdominalis* and *Pseudocalanus* spp., were abundant in the central bay area in the same periods (Figs. 7, 8E; Takatsu *et al.*, 1992), where bottom water temperatures were relatively low (about <9°C, Fig. 4). It is possible that the settlement of juveniles mainly occurred in shallow waters (about 30 m depth) along the coast of Mutsu Bay, and then juveniles migrated to deeper areas when in water temperature increased and calanoid abundance decreased in shallow waters (Fig. 8B, 8E).

Cod larvae and pelagic juveniles were rarely found at the bay mouth in April (Figs. 2, 8D), whereas some juveniles were distributed at the bay mouth in May 1989 (Figs. 4, 8E). Scientists at the Aomori Prefectural Fisheries Experimental Station carried out cod juveniles' samplings with a beam trawl net (5 m mouth width and 21 mm mesh in 1997 and 1998) and an otter trawl net (9 m mouth width in 1999) on the bottom in the northern part of the bay mouth (Fig. 1) from early June to early September in 1997–1999 (G. Odagiri, Aomori Prefectural Fisheries Experimental Station, personal communication). The results obtained showed that CPUEs of cod juveniles were highest in late June, but low in early June and July. It is thus likely that some juveniles start to migrate outside of the bay from mid- and late May, and many juveniles migrate outside in late June. Adult and immature Pacific cod mainly occurred at temperatures <12°C (Uchida, 1936, Kawamura and Kokubo, 1950, Hashimoto, 1974). Cod juveniles in July feed mainly on gammarid amphipods and juvenile walleye pollock (*Theragra chalcogramma*; Takatsu *et al.*, 1995). Most gammarids were distributed at the bay mouth in July

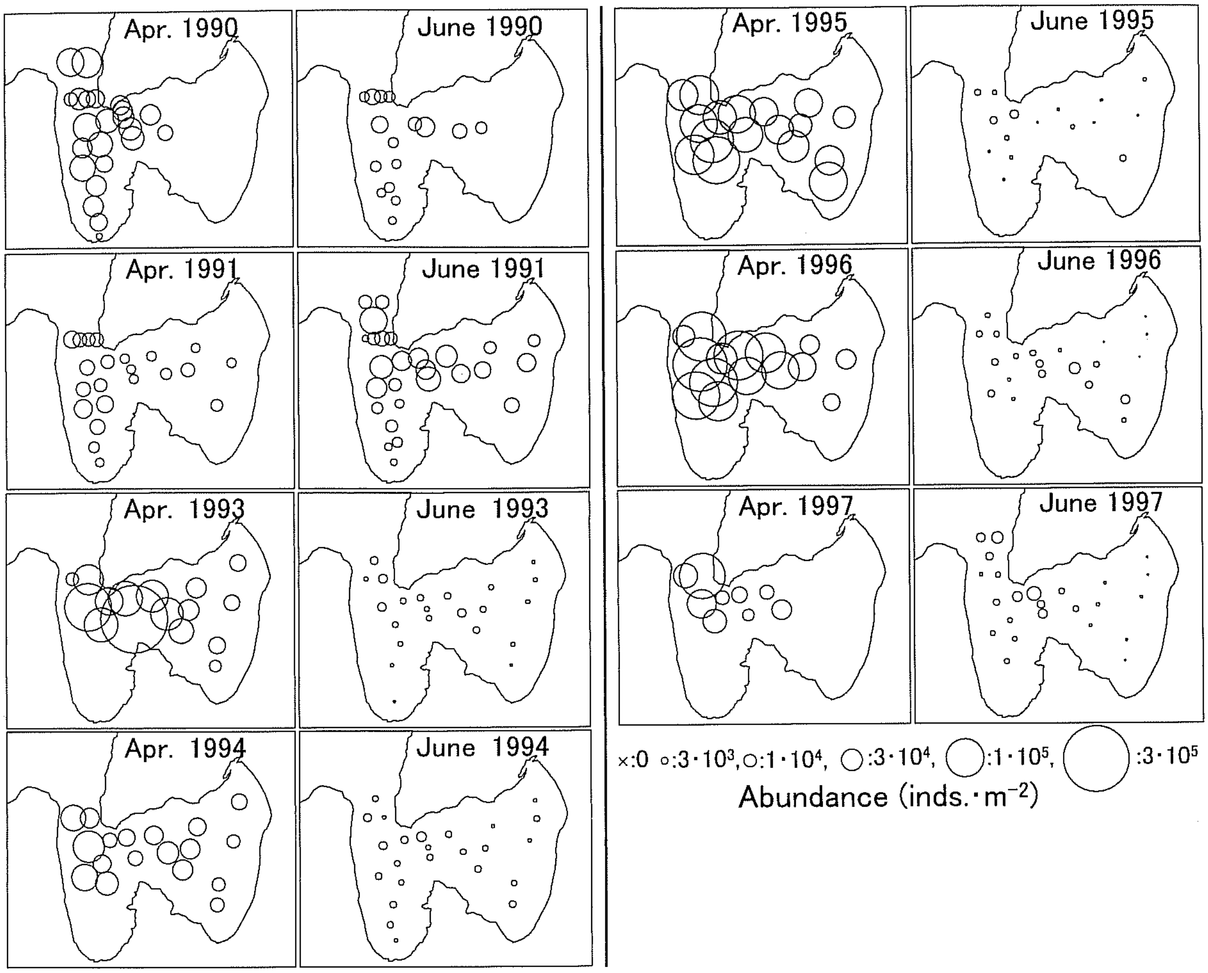

Figure 7. Horizontal distribution of calanoid copepodites collected by vertical hauls from the sea bottom to the surface with a NORPAC net (0.33 mm mesh) in April and June in 1990, 1991 and 1993–1997.

1988 (Figs. 5, 8C). Juvenile walleye pollock migrate outside of Mutsu Bay after June (Takatsu *et al.*, 1992). Thus, high water temperatures and low prey abundance make Mutsu Bay unsuitable for cod juveniles in July. Cod use Mutsu Bay as a nursery ground, and calanoid copepodites sustain cod larvae and juveniles as their prey until mid-June.

A positive correlation was found between landings of spawners and mean densities of larvae and pelagic juveniles in April in Mutsu Bay, except for the 1995 year-class (Fig. 6A). It is possible that mortality from the egg stage to pelagic juvenile stage does not differ much in usual years if the hatching periods are fixed annually. A remarkable result was that no eradicated year-class (low density of larvae and juveniles in April despite high abundance of spawners) was found (Fig. 6A). In April 1995, mean density of larvae and juveniles was high in spite of the low abundance of spawners, and the 1995 year-class would have low mortality in the pelagic larval stage. A high abundance of calanoids in April was found not only in 1995 but in 1993 and 1996 (Fig. 7). No extraordinary condition of water was found in the bay from January to March in 1995 (Aomori Prefectural Aquaculture Research Center, 1992-1999). We do not have data on the abundance in copepod nauplii and copepodites from January to March in 1995. Thus, the cause of this event is unclear.

There was no correlation between landings of spawners and mean densities of Pacific cod juveniles in June (Fig. 6B). In addition, no correlation was found between mean densities in April and June among sampling years. Large differences in mortality would occur in the transition from a pelagic to a demersal distribution between April and June from year to year. The demand for calanoid prey by juveniles will increase as the juveniles grow, but calanoid abundance was lower in June than in April every year except 1991. In June of most years, juveniles may have a low growth rate due to low prey amounts and may be exposed to predation by demersal piscivorous fishes.

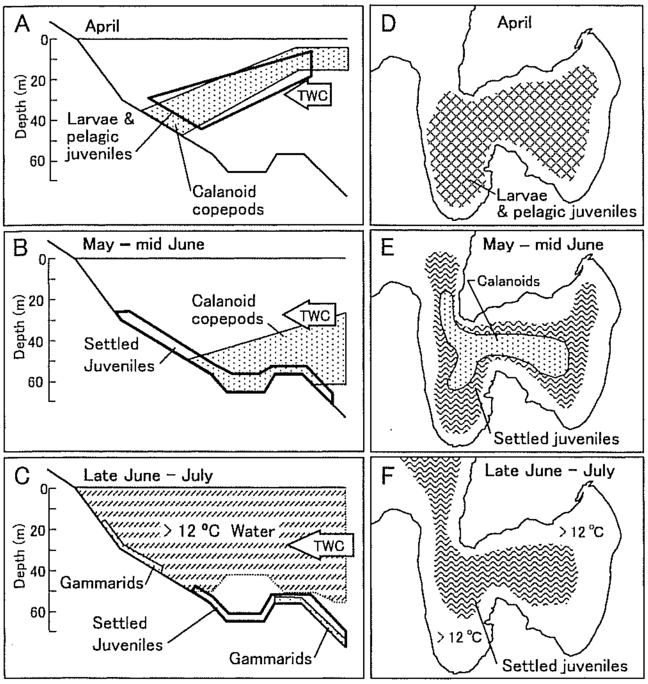

Figure 8. Schematic model of vertical (A–C) and horizontal distribution (D–F) of Pacific cod larvae and juveniles, and their food organisms in Mutsu Bay and its bay mouth from April to July. TWC in each figure indicates that the Tsugaru Warm Current enters the bay. A patch of calanoid copepodites in mid- and late May (Takatsu *et al.*, 1992) and June (Fig. 7) is shown in figure E.

In 1991, cod juveniles and calanoid copepods were the most abundant in June (Figs. 6B, 7). In February 1991, a small regional difference in water density brought the small inflow of the Tsugaru Warm Current (Takatsu *et al.*, unpublished). Less saline water was stagnated at the surface in April and June 1991. The slow increase in water temperature was caused by the small inflow of TWC in April and June 1991 (Fig. 4), and the peak period of calanoid abundance might have occurred after April in 1991 (Fig. 7). Because the mean calanoid abundance was low in spite of the low water temperature in June 1996, low water temperature would be a necessary, but not sufficient, factor to maintain a high abundance of calanoids in Mutsu Bay in June. Low exchange of water masses, low water temperatures, and high abundance of calanoids in June 1991 were thought to be suitable for cod survival, but prevented juveniles from leaving the bay. The age at first maturation of female cod in Mutsu Bay was estimated to be four years (Hattori *et al.*, 1992). The 1991 year-class would not be the dominant year-class, because commercial landings of adult cod in 1995-1997 were low (Aomori Prefectural Aquaculture Research Center, unpublished; Fig. 6). It is possible that the 1991 year-class decreased in abundance in and/or outside of the bay after mid-June 1991.

No year-class was found to have low mortality through the larval and juvenile stages in Mutsu Bay and outside of the bay from 1990 to 1997, and commercial catches of adult Pacific cod have drastically decreased at the bay mouth of Mutsu Bay after 1990 (Aomori Prefectural Aquaculture Research Center, unpublished). Our results suggest that cumulative mortality during pelagic and settled juvenile stages after April is an important factor affecting the subsequent year-class strength, rather than relatively instantaneous mortality at the first-feeding stage before March. Predation mortality associated with growth rate may be more important than starvation as a regulator of recruitment (Houde, 1987, Watanabe *et al.*, 1995, Campana, 1996). We need further investigations on the growth rate and predation mortality of Pacific cod juveniles in Mutsu Bay and outside of the bay after April. In addition, we need improved sampling gear and practical filtration efficiency of both trawl nets to accurately estimate the mortality rate during the pelagic and demersal juvenile stages of Pacific cod.

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陸奥湾におけるマダラ稚魚の時空間分布

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1988–1997年4–7月に，陸奥湾においてマダラ稚魚とその餌生物の時空間分布を調べた．4月には大型仔魚（全長25 mm以下）と浮遊稚魚 (>25 mm) は湾内に広く分布し，昼間はカラヌス目かいあし類の高密度分布層に集中した．仔稚魚の体サイズの地理的変異は，津軽暖流水による輸送により生じたものと推定された．5月中下旬以降稚魚とカラヌス目は海底直上に出現した．4月と6月の稚魚の平均個体数密度は年によって大きく変動し，稚魚の高い個体数密度はカラヌス目の高い豊度とともにみられた．湾内の水温上昇と餌豊度が低下する6月下旬以降，稚魚は水温12°Cを超える水域にほとんど出現せず，湾外に移動すると考えられた．マダラは陸奥湾を生育場として利用し，カラヌス目コペポダイトは6月中旬まで仔稚魚の餌生物として生残を支える．陸奥湾におけるマダラ仔稚魚の死亡率の変動は，主に4月の浮遊稚魚期以降に生じたものと思われる．

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