
Mitsuhiro Nagata1, Yasuyuki Miyakoshi1, Daisei Ando1, Makoto Fujiwara1, Mayumi Sawada2, Hiroshi Shimada2, and Hiroki Asami3

1Hokkaido Fish Hatchery, Kitakashiwagi-3, Eniwa, Hokkaido 061-1433, Japan
2Hokkaido Central Fisheries Experimental Station, Hamanaka-238, Yoichi, Hokkaido 046-8555, Japan
3Hokkaido Wakkanai Fisheries Experimental Station, Suehiro 4-5-15, Wakkanai, Hokkaido 097-0001, Japan


INTRODUCTION

The number of adult hatchery-origin chum salmon (Oncorhynchus keta) in Hokkaido increased from ~10 million in the middle 1970s to ~40 million in the 1980s as a result of successful hatchery programs and favorable ocean conditions (Kaeriyama 1999). During the 1990s, the chum population fluctuated between 27 and 65 million with marine survivals varying between 2.6 and 5.9% (Nagata and Kaeriyama 2004). Marine survival differs among areas. Recent survival for salmon returning to the Okhotsk Sea has been much higher than those for fish returning to the Japan Sea and the Pacific Ocean regions of Hokkaido. As well, early migrating chum survived at higher rates than late-run groups (Nagata et al. 2004).

Salmon recruitment is determined largely by early mortality (Bax 1983; Willette et al. 2001; Fukuwaka and Suzuki 2002; Mueter et al. 2002). The match or mismatch between the release of larvae and the production of their food influences recruitment success (Cushing 1990). Pink salmon (O. gorbuscha) survivals in Prince William Sound were high in years of extended copepod blooms (Willette et al. 2001). In Hokkaido, chum salmon populations have been maintained by hatcheries with similar numbers of juveniles released (approximately one billion) every year during the past twenty years. Because chum returns varied during this period, we hypothesize that these fluctuations were caused by coastal water conditions that affect food production and predation. If our hypothesis is true, it may be appropriate to alter stocking strategies to reduce variations in the numbers of returning chum salmon. Hokkaido hatchery managers typically release chum juveniles when coastal seawater temperatures are between 5 and 13°C (Seki 2005). In order to evaluate the influence of temperature at the time of release, we investigated the spatial distribution, growth and diet of hatchery-produced chum salmon in relation to coastal water conditions, especially temperature.
MATERIALS AND METHODS

**Otolith Marking and Fry Release**

Approximately 34 million hatchery chum juveniles are released annually into the Abashiri River, usually during May (Fig. 1). To investigate how abundance, distribution, and growth are influenced by the coastal environments, eyed-eggs were marked by immersion in 200 ppm alizarin complexone (ALC) solution for 24 h as described by Tsukamoto (1988) and Nagata et al. (1995). Small single (S), large single (L) and double (D) band ALC otolith marks were produced (Table 1).

To evaluate inter-annual differences, we used eyed eggs fertilized in mid to late October that were marked with S (2003, 2004) or L (2002) bands and fed artificial feed in raceway ponds. Mean fork lengths (MFL) and body weights (MBW) from 2002 to 2004 were 46.6 mm and 0.87 g, 47.5 mm and 0.96 g, and 48.0 mm and 1.08 g, respectively. In mid May of 2002, 2003, and 2004, 2 million, 1.4 million, and 0.8 million, respectively, marked juveniles were released at Lake Abashiri near the outlet of the Abashiri River (Fig. 1).

Additional releases were made in 2003 and 2004 to investigate the influence of the timing of release on distribution patterns and growth. One million marked juveniles (47.5 mm MFL and 0.99 g MBW) with an L band in the otolith were released in late April 2003 to compare with fish released in mid May the same year. In 2004, eggs that had been incubated in low and high temperature water to produce two groups of similar sized individuals were released in mid May (0.9 million L-marked juveniles, 46.8 mm MFL and 0.90 g MBW) and late May (0.7 million D-marked juveniles, 47.9 mm MFL and 0.97 g MBW), respectively.

**Sampling Survey and Biological Analysis**

Twelve study sites were established along 3 transects on the Abashiri coast (Fig. 1). Four sites (A1, B1, C1 and D1) were along a transect 1 km offshore, 4 sites (A2, B2, C2 and D2) were 4 km offshore and the final 4 sites (A3, B3, C3 and D3) were 7 km offshore. Water depths at the transects 1, 4, and 7 km offshore were 10–15 m, 20–30 m, and 30–40 m, respectively. Juvenile chum were collected with a surface trawl net (8-m-wide x 5-m-deep mouth, 18 m long with wing nets 7 m long and a central bag with 5-mm mesh) towed through the 1–2 m surface layer for 1–2 km at 4–6 km/h during the day (5:00–14:00) at intervals of 10 days from late April to early July (2004) or to mid July (2002 and 2003). Rough weather prevented sampling on a few occasions. One additional site at the Abashiri fishing port was sampled in

![Fig.1. Maps showing the study sites at the fishing port (F), the littoral area (E), and 1 km, 4 km and 7 km off the Abashiri coast (A–D) in the Okhotsk Sea. Arrow shows the release site for ALC-marked chum juveniles.](image)

**Table 1.** Date, number and fish size of alizarin complexone (ALC)-marked chum salmon juveniles stocked in the Abashiri River from 2002 to 2004. Recapture rate of each marked group in the coastal and littoral waters from 2002 to 2004. Recapture rate was computed as the number of recaptured juveniles to one million marked juveniles.

<table>
<thead>
<tr>
<th>Marked group¹</th>
<th>Date of fertilization</th>
<th>Date of release</th>
<th>Stocked number of marked fish</th>
<th>Mean fork length (mm)</th>
<th>Mean body weight (g)</th>
<th>Number of recaptured fish</th>
<th>Recapture rate (number / million juveniles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALC (L)</td>
<td>26 Oct. 2001</td>
<td>17 May 2002</td>
<td>2,009,000</td>
<td>46.62</td>
<td>0.87</td>
<td>1,923</td>
<td>957</td>
</tr>
<tr>
<td>ALC (L)</td>
<td>23 Sep. 2002</td>
<td>28 Apr. 2003</td>
<td>1,870,000</td>
<td>47.46</td>
<td>0.99</td>
<td>779</td>
<td>363</td>
</tr>
<tr>
<td>ALC (S)</td>
<td>24 Oct. 2002</td>
<td>15 May 2003</td>
<td>1,385,000</td>
<td>47.48</td>
<td>0.96</td>
<td>794</td>
<td>573</td>
</tr>
<tr>
<td>ALC (S)</td>
<td>15 Oct. 2003</td>
<td>16 May 2004</td>
<td>784,000</td>
<td>47.95</td>
<td>1.08</td>
<td>611</td>
<td>779</td>
</tr>
<tr>
<td>ALC (L)</td>
<td>15 Nov. 2003</td>
<td>16 May 2004</td>
<td>886,000</td>
<td>46.79</td>
<td>0.90</td>
<td>379</td>
<td>428</td>
</tr>
<tr>
<td>ALC (D)</td>
<td>15 Nov. 2003</td>
<td>30 May 2004</td>
<td>671,000</td>
<td>47.90</td>
<td>0.97</td>
<td>88</td>
<td>131</td>
</tr>
</tbody>
</table>

¹ L, S and D represent single large ALC-banding, single small ALC-banding and double ALC-banding marks, respectively.

² The number shows the sum of fish recaptured from 1 km to 7 km.
late May 2003 with a trawl net that was towed for 0.5 km.

Use of the nearshore littoral zone was evaluated using a beach seine (3.5-m-wide x 2-m-deep mouth, 10 m long with wing nets 3 m long and a central bag with 3-mm mesh) from 2002 (only in late May) to 2004. Five seine sets were usually made, starting 100 m offshore, at intervals of 50–100 m along the beach.

Captured fish were sacrificed by an overdose of MS 222 to prevent regurgitation or defecation, preserved in 5% neutralized freshwater formalin, and transferred to 70% ethanol after 12–24 h. Some fish were released soon after they were measured. Catch per unit effort (CPUE) for the surface trawl net was expressed as the number of chum juveniles caught per 2-km tow.

Chum juveniles at each study site were measured for fork length and wet body weight, to the nearest 1 mm and 0.01 g, respectively. Otoliths were examined for ALC-marks using ultraviolet (UV)-light microscopy without polishing the otolith surface except when it was difficult to identify different marks because the surface of otolith was unclear. Full and empty stomachs were weighed to the nearest 0.0001 g to calculate the weight of stomach contents. The percent stomach content index (SCI) was calculated as: (weight of stomach contents / body weight) x 100. Diet composition was determined using a binocular microscope.

**Statistical Analysis**

Arcsin square-root transformed fork length and SCI data were compared by one-way analyses of variance (ANOVA). Specific growth rates were calculated as the slope (b) of the growth curve \( L_t = a e^{bt} \), where \( L_t \) is the fork length at time \( t \). We used fork lengths of marked juveniles at release and recapture and compared among groups and years using analysis of covariance (ANCOVA). When significant differences were found, multiple comparisons were made using Scheffe’s test (Zar 1984).

Electivity indices (E) for food preference were calculated as \( E = (ri - pi) / (ri + pi - 2ripi) \), where \( ri \) is the proportion of i prey animal consumed by fish and \( pi \) is the proportion of the i animal available at a study site (Jacobs 1974). Electivity ranged from -1 to +1; -1 indicates the strongest negative preference, +1 the strongest positive preference. Zooplankton data collected at the coastal study sites and reported by Asami et al. (2007) were used for analysis.

![Fig. 2. Changes in mean values of SST and salinity at the littoral sites, and the 1-km, 4-km and 7-km offshore transects in the Okhotsk Sea from 2002 to 2004. Bars indicate standard errors.](image-url)
RESULTS

SST and SSS

Sea surface temperatures (SSTs) increased seasonally at all sites, except in 2002, which experienced cooling in late June that persisted until early July. Two thousand three was generally cooler than 2002 and 2004 until late June. Water in the littoral area warmed up more rapidly than offshore waters (Fig. 2).

Differences in sea surface salinity (SSS) among sites and locations were less pronounced than temperature differences (Fig. 2). SSSs generally increased as the seasons progressed.

Distribution and Numbers of Juveniles

Although sampling effort was relatively constant among years, far fewer fish were captured in coastal waters from May to July 2003 (~40,300) than in the other two years (~72,000 in 2002 and ~61,600 in 2004). In contrast, the number of juveniles in littoral waters in 2003 was ~11,900, exceeding the ~1,000 caught in 2004.

CPUEs for unmarked chum were generally highest in June, and decreased with distance from shore (Fig. 3). CPUEs at the 4- and 7-km offshore transects peaked later than those 1 km offshore. Almost no unmarked juveniles were captured in May 2003 when SST was < 8°C. However, in May many juveniles were found in littoral areas and at the fishing port (only one survey in late May). Chum abundance in May 2004 in the

Fig. 3. Changes in CPUE (catch per unit effort, the number of juveniles per 2 km towing or per beach seine) of unmarked juvenile chum salmon captured at the littoral sites (beach seine), and at the 1-km, 4-km and 7-km offshore transects (trawl net) in the Okhotsk Sea from 2002 to 2004.
Fig. 4. Changes in CPUE (catch per unit effort, the number of juveniles per 2 km towing or per beach seine) of marked juvenile chum salmon captured at the littoral sites (beach seine), and at the 1-km, 4-km and 7-km offshore transects (trawl net) in the Okhotsk Sea from 2002 to 2004. Arrows indicate time of release.
littoral zone was much lower than that in 2003. Unmarked juveniles in littoral waters were rarely caught after late June 2003 and mid June 2004, and had disappeared from coastal waters by mid July 2002 and 2003, and late June 2004.

Marked juveniles released in mid May 2002 and 2004 were first recaptured at the 1-km offshore transect in late and mid May, respectively (Fig. 4). In contrast, marked juveniles released in mid May 2003 were not recaptured in coastal waters until early June when SSTs were $>8^\circ C$. Fish released in late April of the same year were recaptured in littoral areas in mid/late May. Marked chum rapidly disappeared from coastal waters after late June when SSTs were $>13^\circ C$, (e.g. marked juveniles released in late May 2004 remained in coastal waters for only three weeks).

Fig. 5. Relationships between SST and CPUE in chum salmon including marked juveniles captured at the littoral sites (beach seine), and the 1-km, 4-km and 7-km offshore transects (trawl net) in the Okhotsk Sea from 2002 to 2004.

Fig. 6. Changes in mean fork length of unmarked juvenile chum salmon captured at the littoral sites, and the 1-km, 4-km and 7-km offshore transects in the Okhotsk Sea from 2002 to 2004. Bars indicate standard errors. Values not sharing a common small letter among years are significantly different at $p < 0.05$. 

NPAFC Bulletin No. 4
Nagata et al.
Influence of temperature on distribution and growth of chum salmon

Recapture rates (number of fish captured per one million released) in coastal waters varied between 131 and 957 (Table 1). The highest recapture rate (957) was recorded for L-marked juveniles released in mid May 2002, and the lowest (131) for D-marked juveniles released in late May 2004.

In the littoral waters, recapture rates in both 2003 and 2004 varied between 0 and 194.

Growth Rates

Mean fork lengths (MFL) of unmarked chum juveniles at the 1-km offshore transect in 2002 ranged between 50 and 60 mm until mid June, increasing gradually thereafter, reaching 70 mm in mid July (Fig. 6). In contrast, MFLs at the 4- and 7-km offshore transects increased sharply from mid to late May when CPUEs increased, reaching 75 mm and 80 mm in late June. As a result, there were significant differenc-

Table 2. Specific growth rate (SGR) of each marked group captured 1 km off the coast (A1–D1) about 3 weeks after release from 2002 to 2004.

<table>
<thead>
<tr>
<th>Year</th>
<th>ALC mark</th>
<th>At release</th>
<th>At recapture</th>
<th>Δ t</th>
<th>SGR</th>
<th>SGR (slop b, ( L_t = a e^{bt} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Date</td>
<td>MFL (mm)</td>
<td>Date</td>
<td>MFL (mm)</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>L</td>
<td>May 17</td>
<td>46.62</td>
<td>June 6</td>
<td>52.94</td>
<td>20</td>
</tr>
</tbody>
</table>
| 2003 | L        | April 28   | 47.46        | May 22 | 53.69 | 24 | 0.0051 | 3
|      | S        | May 15     | 47.48        | June 4 | 59.20 | 37 | 0.0060 |
| 2004 | S        | May 16     | 47.95        | June 8 | 59.33 | 23 | 0.0093 |
|      | L        | May 16     | 46.79        | June 8 | 57.26 | 23 | 0.0088 |
|      | D        | May 30     | 47.90        | June 17 | 55.94 | 18 | 0.0086 |

* L, S and D represent single large ALC-banding, single small ALC-banding and double ALC-banding marks, respectively.
* SGR = \( (\ln(L_{t2}) - \ln(L_{t1})) / (t_{2} - t_{1}) \), \( L_t \) is MFL (mean fork length).
* SGR was computed using marked fry captured at the fishing seaport near B 1, because no samples were taken 1 km off the coast on May 22, 24 days after release. First capture was on June 4, 37 days after release.

Table 3. Specific growth rates as the slope of the exponential equation computed using individual fork length in marked groups captured after release from 2002 to 2004.

<table>
<thead>
<tr>
<th>Year</th>
<th>ALC mark</th>
<th>At release</th>
<th>SGR (slop b, ( L_t = a e^{bt} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Date</td>
<td>Littoral water</td>
</tr>
</tbody>
</table>
| 2002 | L        | May 17     | 46.62        | 0.0058 | 0.0107 | 2
| 2003 | L        | April 28   | 47.46        | 0.0023 | 0.0069 | 0.0078 |
|      | S        | May 15     | 47.48        | 0.0010 | 0.0077 | 0.0100 |
| 2004 | S        | May 16     | 47.95        | -0.0119 | 0.0094 | 0.0124 |
|      | L        | May 16     | 46.79        | 0.0090 | 0.0116 | 4
|      | D        | May 30     | 47.90        | 0.0090 | 0.0124 | 4

* L, S and D represent single large ALC-banding, single small ALC-banding and double ALC-banding marks, respectively.
* The values not sharing a common small letter between 1 km and 4&7 km offshore are significantly different. The values not sharing a common large letter among different groups in each offshore area are significantly different \((p < 0.05)\).
es in MFL between the 1-km and the 4- and 7-km offshore transects. In 2003, MFL of chum juveniles in each transect increased rapidly after early June when CPUEs increased. In 2004, MFL of juveniles at each transect increased rapidly after mid May (when CPUEs also increased), reaching 70–80 mm in mid June, except for those at the 1-km offshore transect. These data indicate that MFLs of juveniles in 2002 and 2004 under warmer conditions increased earlier than those in 2003 when temperatures were cooler. MFLs of chum captured in littoral waters were similar to or smaller than those at the offshore transects, and did not increase.

SGRs of marked juveniles during early periods (18 to 37 d after release) at the 1-km offshore transect where CPUEs were highest ranged from 0.0051 to 0.0093 (Table 2). SGRs for marked juveniles released in 2002 and 2003 varied between 0.0051 and 0.0064, lower than those (0.0086–0.0093) in 2004; in particular, SGR of juveniles released in late April 2003 was 0.0051 at 24 d post-release, and 0.0060 at 34 d post-release, lower than any others. Throughout the survey, SGRs of marked juveniles collected at the littoral sites in 2003 and 2004 were significantly lower than those in coastal waters (Table 3). SGRs for most fish caught at the 1-km transect were highest in 2004. SGRs at the 4- and 7-km offshore transects were significantly higher than those in littoral waters and at the 1-km offshore transect, indicating either that offshore chum grow fastest, or that larger chum move offshore. Although there were no significant differences in SGRs in 2003 between early (mid May) and late May released groups, MFL at the 1-km offshore transect were larger in the early released group (63–64 mm) than in the late released group (56 mm).

Stomach Contents

Mean stomach content indices (SCI, stomach content weight x 100 / body weight) for unmarked juvenile chum at the 1-km offshore transect were relatively high for the three years, except in 2002 when there was a decrease in June (Fig. 7). Although the SCI at the 4-km offshore transect were also relatively high, they decreased sharply in mid to late June. In contrast, SCI at the 7-km offshore transect were relatively high in June, especially in 2004. These changes in the composition of stomach contents were also observed in marked juveniles, except at the 7-km location where few samples

![Fig. 7. Changes in mean values of stomach content indices (stomach content weight x 100 / body weight) of unmarked (top) and marked (bottom) juvenile chum salmon captured at the littoral sites and the 1-km, 4-km and 7-km offshore transects in the Okhotsk Sea from 2002 to 2004. Bars indicate standard errors. The values not sharing a common small letter among years (marked juveniles only) are significantly different at p < 0.05.](image-url)
were taken. In littoral waters, SCI of juveniles with high CPUE in May 2003 were significantly lower than those in 2004 with lower CPUE.

Diet analysis of both unmarked and marked juveniles revealed that offshore juvenile chum in 2002 consumed primarily cold-water species of copepods (mainly small coastal species such as *Pseudocalanus newmani* and large oceanic species such as *Neocalanus* spp.) and appendicularians (mainly *Fritillaria borealis* f. *typica*) in May, switching to warm-water small species such as cladocerans (mainly *Podon leuckarti* and *Eudale nordmannii*) and appendicularians (mainly *Oikopleura longicauda*) in June (Fig. 8). Beginning in late June, various amphipods, insects and fish eggs were consumed. Electivity indices showed that chum in 2003 initially favored copepods, but later switched to cladocerans and appendicularians. Diet composition of chum juveniles in the littoral zone in 2003 was different from that in coastal waters. Juveniles in the littoral zone consumed not only small pelagic copepods such as *P. newmani* but also small epibenthic crustaceans such as Harpacticoid copepods and amphipods, indicating that juvenile chum can change feeding behavior depending on nursery conditions. In 2004, the main diet at the offshore transects consisted of large copepods such as *Neocalanus* spp. After mid June when SSTs were warmer, feeding on copepods decreased, and more cladocerans, amphipods and fish eggs were added to the diet. Indices revealed that chum preferred copepods over cladocerans, unlike preferences in 2002 and

![Diagram](image-url)

**Fig. 8.** Changes in diet composition (by number) including both unmarked and marked juvenile chum salmon at the littoral sites and the 1-km, 4-km and 7-km offshore transects in the Okhotsk Sea from 2002 to 2004.
Consequently, SST in May 2003 ranged from 5.3 to 6.8°C, Abashiri coast was delayed (Asami et al. 2007), allowing the
movement of the Soya Warm Current toward the
In 2003, the movement of the Soya Warm Current toward the
...year. In the warmer years, 2002 and 2004, when
sea ice disappeared in 2002 and 2004 in early March, one
...year. We found that chum salmon
...extending from littoral waters to 1 km offshore are important
...important nursery areas for chum juveniles. Juvenile chum are known
to live in estuaries and littoral areas for long periods, and
...colder than in the warmer years 2002 and 2004.

Relatively high abundances of juvenile chum salmon
were found in littoral waters and at the 1-km offshore transects from May to June each year. Lower abundances were
recorded at the 4- and 7-km offshore transects. Fish were
most abundant after May, and largest, at the transects farthest from shore. We conclude that the relatively large area
extending from littoral waters to 1 km offshore are important
nursery areas for chum juveniles. Juvenile chum are known
to live in estuaries and littoral areas for long periods, and
then move offshore as SSTs increase and fish grow larger
(Kaeriyama 1986; Irie 1990). We found that chum salmon
juveniles showed remarkable differences in spatial distribution
year by year. In the warmer years, 2002 and 2004, when
SST in the coastal waters exceeded 8°C in May, most un-
marked chum juveniles were found near the 1-km offshore transect, not in littoral waters. This contrasts with the cooler
year, 2003, when SST did not exceed 8°C in May. In 2003

Fig. 9. Changes in electivity indices (by number) for four prey groups by juveniles including both unmarked and marked chum. Electivity (Jacobs, 1974): 
\[ E = \frac{(ri - Pi)}{(ri + Pi - 2ri \cdot Pi)} \]
ri: % of i species in stomach contents; Pi: % of i species at the offshore transects. +1 = positive preference; -1 = negative preference.

2003. Amphipods (mainly Themisto japonica) were favored
by chum throughout the season in 2002–2004. Diet at the
littoral sites in 2004 differed from that in 2003, being domi-
nated by pelagic copepods such as Neocalanus spp. and E.
herdmani.

DISCUSSION

Although the Okhotsk Sea is usually covered with sea
ice during the winter, the maximum coverage, and dates of
arrival and disappearance varies year by year (Shimizu 2005).
The sea ice disappeared in 2002 and 2004 in early March, one
month earlier than in 2003 that saw the latest disappearance
date in the past 10 years (Shimizu 2005; Asami et al. 2007).
In 2003, the movement of the Soya Warm Current toward the
Abashiri coast was delayed (Asami et al. 2007), allowing the
cold Okhotsk Surface Water to occupy the study area longer.
Consequently, SST in May 2003 ranged from 5.3 to 6.8°C,
chum remained either in littoral waters or at the fishing port for an extended period before moving 1 km offshore. These results suggest that coastal seawater temperatures may affect the behavior of chum juveniles soon after their seaward migration. This idea is strongly supported by the fact that marked juveniles released in late April 2003 were captured only in littoral waters or at the fishing port in May, and were first found in early June at the 1-km offshore transect. We suggest that juvenile chum salmon show two types of marine dispersal patterns that are influenced by SSTs. When offshore waters are < 8°C, many juvenile chum remain in littoral waters at 1–2 m depth or at the fishing port for extended periods. When offshore waters are > 8°C, many chum disperse rapidly to the 1-km offshore transect and remain there for a relatively long time before moving farther offshore.

These two temperature-related patterns affect growth and recapture rates. Marked juveniles in 2003 and 2004 grew poorly when they lived in littoral waters. Juveniles densely aggregated in littoral waters in 2003 fed poorly (lower SCIs) and consumed predominantly small epibenthic copepods, compared to the juveniles that were more widely dispersed in 2004. In addition, marked juveniles that moved 1 to 7 km offshore in 2003 generally grew more slowly than juveniles released in 2002 and 2004. It appears that when chum juveniles aggregate densely in the relatively narrow littoral and estuarine areas at colder temperatures, feeding and growth may be reduced due to shortages of food and/or low temperatures. This period of littoral or estuarine residence of chum juveniles may strongly affect early ocean survival.

The offshore movement of chum juveniles occurred from late June in 2004 to mid July in 2002 and 2003, coinciding with SST > 14–15°C and MFLs between 60 and 80 mm. Chum juveniles move offshore when SST, salinity and fish size exceed 13–14°C, 33.5–34.0 psu, and 70 mm FL, respectively (Mayama et al. 1982; Mayama 1985; Kaeriyama 1986). Our observations are consistent with previous research. Kaeriyama (1986) identified influences on offshore migration: an active migration to search for prey, and a passive migration arising from lack of food or escape from unsuitable environmental conditions such as high SST. Marked juveniles released in late May 2004 left coastal waters early despite a rapid growth rate because SSTs exceeded 14°C and prey abundance was low (Asami et al. 2007). In addition, recapture rates and fish sizes before moving offshore for late releases were less than those for early releases. These results support Kaeriyama’s hypothesis. Recent survival for salmon returning to the Okhotsk Sea is known to be much lower in late-run chum than in early-run chum (Nagata et al. 2004). As hatchery juveniles from the late-run chum were released later (from late May to early June) they may have encountered unfavorable ocean conditions such as high SSTs and a shortage of prey during their shorter residence time in coastal waters. Therefore, recent low survival in the late-run chum might be the result of a mismatch in the timing of release of juveniles and environmental conditions in the ocean. Marked chum salmon released at different periods in 2002–2004 will return as 3- to 5-year-old adults from 2004 to 2009, which will allow us to test this hypothesis.

Optimal SST for releasing hatchery chum juveniles into Hokkaido rivers are between 5 and 13°C (Irie 1990; Mayama and Ishida 2003; Seki 2005). Seki and Shimizu (1996) discovered that return rates for chum juveniles released when coastal water temperatures were > 5°C were 0.216%, much higher than 0.056% when coastal water temperatures were < 5°C. But chum (46 mm FL) released at SST > 5°C were much larger than those (41 mm) released at SST < 5°C. Because mortality in chum salmon juveniles is strongly size-selective (Healey 1982), additional research is needed to conclude whether reduced return rates are caused by cooler temperatures (< 5°C). Some chum juveniles have been observed in coastal waters at 5°C (Irie 1990; Seki 2005), but most are found in coastal waters between 8 and 13°C (Kaeriyama 1986; Irie 1990; Seki 2005), which is consistent with our results. Therefore, it is reasonable to conclude that 5°C is unsuitable for chum juveniles.

Most marked chum salmon moved to the 1-km offshore transect within 10 d after release. Juvenile chum salmon in small streams are known to reach the ocean within 24 h (Iwata and Komatsu 1984; Nagata and Miyamoto 1986). Chum in larger (and longer) rivers reach the ocean within 10 d (Mayama et al. 1982). Therefore, we recommend that chum juveniles be released when coastal waters reach 7°C, enabling them to move rapidly to coastal waters.

It seems reasonable that the upper SST limit for chum juveniles in coastal waters is 13°C; other researchers (Kaeriyama 1986; Irie 1990; Kawamura et al. 2000; Seki 2005) report catching no fish in coastal waters exceeding 14°C. Fish that are 70 mm FL and 3 g BW are thought to have the potential to move actively offshore, based on ecological conditions, and physiological and morphological characteristics (Kaeriyama 1986; Irie 1990). High growth rates of marked juveniles were recorded in 2004 when their diet was dominated by large cold-water copepods such as Neocalanus spp. Neocalanus build a substantial high-energy lipid reserve which is utilized during the subsequent winter for egg development (Cooney 1986). A recent study (Seki, 2005) showed that cold-water zooplankton abundance peaks at 10°C, and then declines rapidly as temperatures increase. At the Abashiri coast, a high abundance of cold-water zooplankton, especially large copepods, was also observed at temperatures below 10°C (Asami et al. 2007). Releases of chum salmon when SST reaches 13°C may be too late to best utilize cold-water copepods. We suggest that the optimal upper SST limit in coastal waters for releasing juvenile chum should be < 11°C. In summary, one should avoid releasing juvenile chum salmon when coastal water temperatures are either < 7°C or > 11°C.
ACKNOWLEDGMENTS

We deeply appreciate Y. Yoshida and staff of the Abashiri Fisheries Cooperative Association, K. Chida and staff of the Abashiri City Science Center and staff of the East Branch of Fisheries Technical Guidance Office for supporting the coastal and beach surveys, and M. Nagase of Aoi Hatchery and staff of the Kitami Salmon Enhancement Programs Association for ALC mass marking and fish production. We also thank T. Kaneko of the Marine Biological Research Institute of Japan Co., Ltd. and M. Iwabuchi of Econixe Co., Ltd. for determination of diet composition. J.R. Irvine of the Pacific Biological Station in Canada made helpful comments on drafts of this manuscript. Further, we thank two anonymous reviewers for their thoughtful comments. The Fisheries and Forestry Department of the Hokkaido Government provided financial support for the sampling program.

REFERENCES


(Available at http://www.npafc.org).