Review of Ocean Salmon Research by Japan from 1991 to 1998

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Abstract: Scientists of the National Research Institute of Far Seas Fisheries, Shimizu, Japan, conducted various surveys on Pacific salmon (*Oncorhynchus* spp.) in the northern North Pacific Ocean and adjacent seas from 1991 to 1998. The major results are summarized as follows: 1) chum salmon (*O. keta*) juveniles originating in Japan occurred in the Okhotsk Sea in summer and migrated into the western North Pacific from fall to winter; 2) growth variation of Pacific salmon was due to both intra- and inter-specific density dependent effects; 3) the abundances of phytoplankton, zooplankton, and Pacific salmon (especially pink salmon *O. gorbuscha*) which varied both temporally and spatially in offshore waters were related to each other, suggesting a top-down control of production; 4) salmon sharks (*Lamna ditropis*) caused a high ocean mortality of Pacific salmon; 5) there was a positive relationship between summer offshore catches of chum and sockeye salmon (*O. nerka*) and their coastal returns, which suggests a possible method of forecasting salmon returns; and 6) Pacific salmon were distributed in lower temperature waters and may be adapted to lower food resources in winter. Issues for future salmon research are discussed.

INTRODUCTION

An international workshop on future salmon research in the North Pacific Ocean was held at the National Research Institute of Far Seas Fisheries (NRIFSF) in Japan on November 11, 1991, just after the last annual meeting of the International North Pacific Fisheries Commission (INPFC). The workshop summary reported that the major focus of research would clearly shift from issues of interception to such problems as stock interaction, climate change, effects of artificial propagation, and carrying capacity of the North Pacific Ocean for Pacific salmon (*Oncorhynchus* spp.) (Ishida et al. 1992). To establish an effective mechanism of international cooperation to promote the conservation of anadromous stocks in the North Pacific Ocean, Canada, Japan, the Russian Federation and the United States of America signed a convention and formed the North Pacific Anadromous Fish Commission (NPAFC) on February 11, 1992 (NPAFC 1993a). At the 1993 Annual Meeting of the NPAFC, the Committee on Scientific Research and Statistics (CSRS) identified the following two critical issues for research by the Parties: 1) factors affecting current trends in ocean productivity, and 2) factors affecting changes in biological characteristics such as growth, size and age at maturity, oceanic distribution, survival, and abundance of Pacific salmon (NPAFC 1993b). The CSRS also developed the NPAFC Science Plan to address these two critical issues by three areas of study: 1) salmonid life history, 2) salmonid population dynamics, and 3) salmonid habitat and ecosystem (NPAFC 1994). The purposes of this paper are to review the results of ocean salmon research conducted by the NRIFSF from 1991 to 1998, and to discuss issues for future research.

Juvenile Salmon Studies

The migration routes and distribution of Japanese juvenile chum salmon (*O. keta*) were surveyed in near shore waters around Hokkaido in northern Japan from 1977 to 1985 (Irie 1990). Migrating juvenile chum salmon were mainly concentrated in areas with surface temperatures from 9 to 13°C and surface salinities from 31.0 to 33.9 psu; the upper limits were about 14°C and 34psu. The juvenile chum salmon originating in the Japan Sea coast and the Pacific coast of Honshu migrated along the coast of Hokkaido during their offshore migration. However, their offshore

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migration routes to the North Pacific Ocean were not identified.

To clarify the offshore migration routes of juvenile salmon, Japan-Russian cooperative surveys were conducted in the waters off southeastern Hokkaido, Sakhalin, and the Kuril Islands, using a purse seine, a surface trawl, dip-nets, and drift nets in the summers of 1988–1992 (Fig. 1). The results suggested two possible migration routes of juvenile chum salmon after they enter the coastal waters: 1) juvenile chum salmon migrate to offshore waters of the Okhotsk Sea, and 2) they migrate within coastal waters near the Kuril Islands (Ueno and Ishida 1996).

To examine the first possible migration route, the NRIFSF conducted drift gillnet and surface trawl operations in the Okhotsk Sea and the Pacific waters off Hokkaido and the Kuril Islands from early summer to late autumn in 1993–1996 (Ueno 1998). The results indicated that juvenile chum salmon mainly occurred in the southern and central waters of the Okhotsk Sea from summer to mid-autumn. Then they migrated out from the Okhotsk Sea to the Pacific waters off the Kuril Islands in late autumn (Fig. 2). Juvenile chum salmon were concentrated in a limited area of the Okhotsk Sea; abundance was estimated at 60–100 million fish in 1993, and 200–334 million fish in 1996 (Ueno 1998).

Stock origins of juvenile chum salmon in the Okhotsk Sea were identified by morphological characters such as pyloric caeca counts and by genetic characters such as allele frequencies (Ueno et al. 1998). The results indicated that juvenile chum salmon from southern stocks such as Japan, Sakhalin, and Primorie migrated northwards through the southern part of the Okhotsk Sea in July and were distributed in the central part of the Okhotsk Sea in August and September. In October and November, they migrated southwards to the central and southern part of the Okhotsk Sea and moved to the North Pacific Ocean through the straits of the northern and central Kuril Islands. Northern Russian stocks such as Magadan and western Kamchatka were distributed in the northern and eastern part of the Okhotsk Sea, and followed the southern stocks (Ueno et al. 1998). Among juvenile chum salmon (age 0.0) caught in the Okhotsk Sea, the Japanese stock was predominant (71%) in October, but its contribution to the sample decreased to 36% in November. Juvenile chum salmon migrating to Pacific waters east of the Kuril Islands in November were composed of 57% Japanese, 30% Russian and 13% Alaskan stocks. Young chum salmon (age 0.1) caught in winter in the western North Pacific Ocean consisted of 29% Japanese, 65% Russian and 6% Alaskan stocks in January and 37% Japanese, 45% Russian and 18% North American stocks in February (Urawa et al. 1998).

In addition to these migration studies, potential predators of chum salmon juveniles off the Japanese coast and in coastal waters of the Kuril Islands were reviewed based on various sources of the literature (Nagasawa 1998a). Two species of seabirds (rhinoceros auklets *Cerorhinca monocerata* and black-tailed gulls *Larus crassirostris*) and two species of fishes (arabesque greenling *Pleurogrammus azonus* and Japanese dace *Tribolodon hakonensis*) were thought to be significant predators.

Fig. 1. Seasonal changes in distribution of juvenile chum salmon caught by research vessels from 1988–1992. Symbols indicate no catch (x) and size of circle indicates abundance of juvenile salmon caught by purse seine, surface trawl, dip net, and drift net. Early summer (a), mid summer (b) and total (c). (Fig. 1 from Ueno and Ishida 1996).

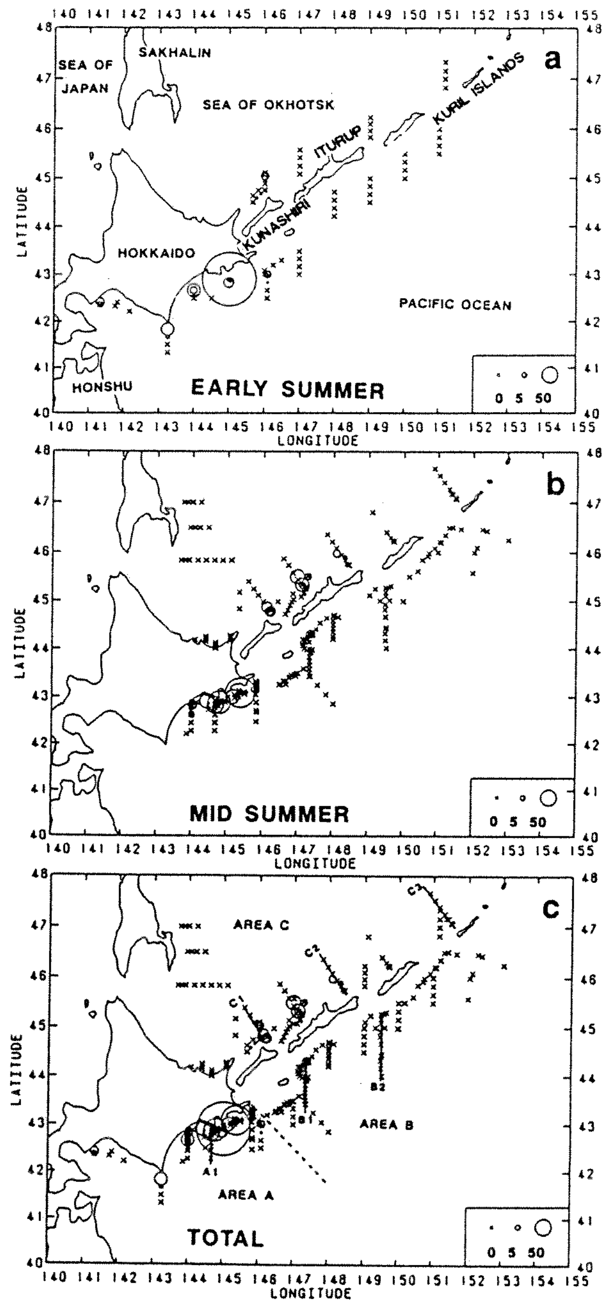
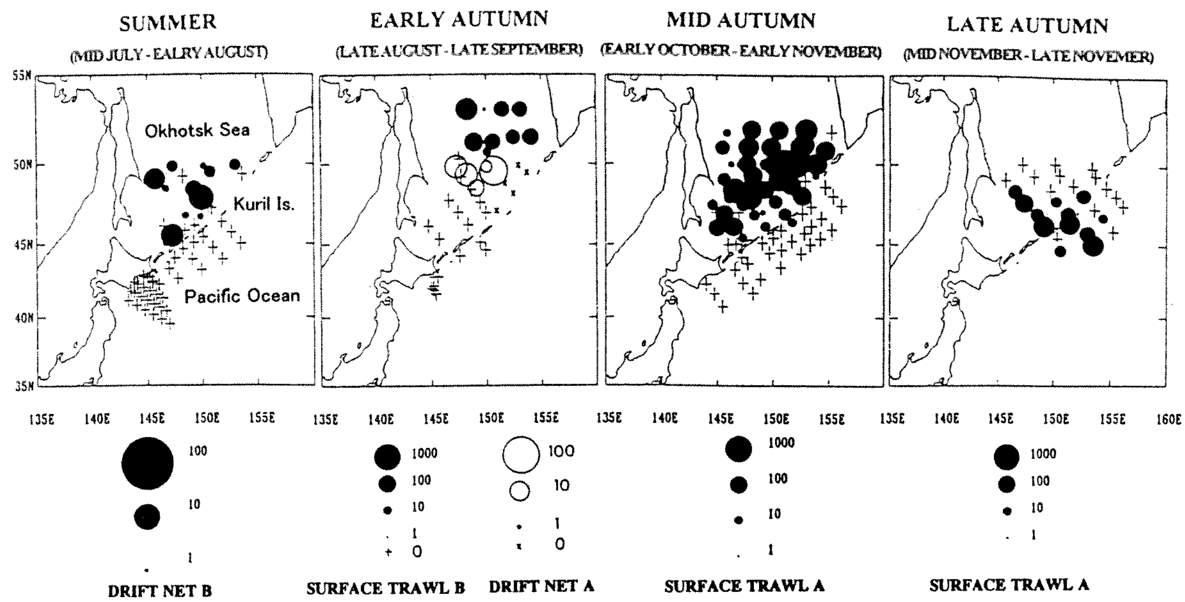


Fig. 2. Seasonal distributions of juvenile chum salmon caught by research vessels from 1993 to 1996. (Fig. 2 from Ueno 1998).



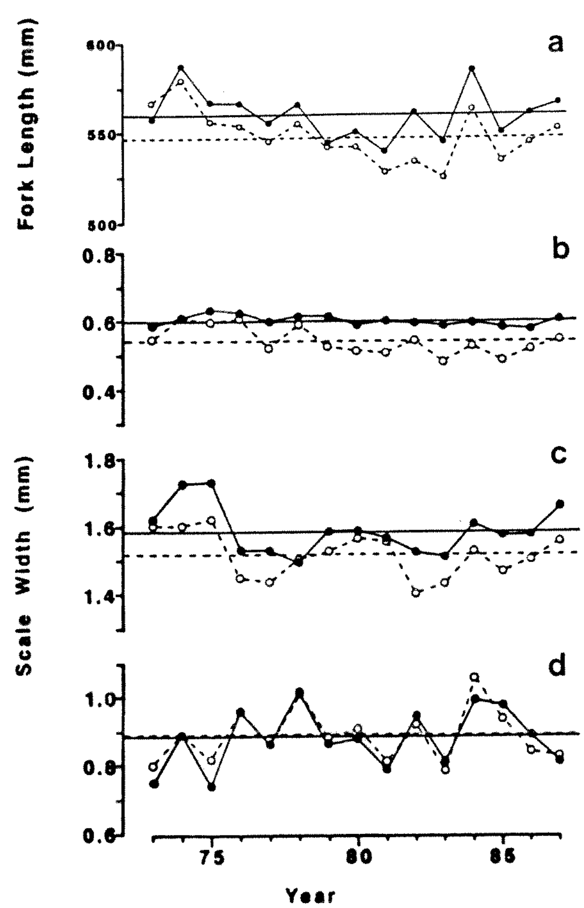
Juvenile salmon studies suggest that the Okhotsk Sea is an important nursery ground for juvenile salmon originating from Russia and Japan. Future issues for the juvenile salmon studies are: 1) assessment of juvenile salmon abundance, 2) stock identification and estimation of stock composition of juvenile salmon by genetic methods and otolith thermal marks, and 3) investigation of factors affecting survival and abundance of juvenile salmon in the Okhotsk Sea.

Salmon Growth Studies

Growth variation of coho salmon (*O. kisutch*) in the western North Pacific Ocean from 1973 to 1987 was examined based on fork lengths and scale measurements (Ogura et al. 1991). Average fork lengths of coho salmon in July in the area of 44°–50°N latitude and 160°E–180° longitude showed long-term variation, decreasing after 1975 and increasing from 1983 to 1987. Growth also showed strong odd-even year fluctuation (Fig. 3-a). The scale measurements indicated that long-term variation of growth occurred during the freshwater period and during the first year of ocean life (Fig. 3-b, c). Substantial odd-even year fluctuation in growth occurred only during the second year of ocean life (Fig. 3-d). These results suggested that intraspecific density-dependent growth is an important factor during the freshwater stage, and interspecific density-dependent growth is important during the second year of ocean life, the latter due primarily to the overlap of diet between coho and pink salmon (*O. gorbuscha*) (Anderson and Wilen 1985; Ito 1964).

Changes in age composition and size of adult chum salmon from rivers in Japan, Russia, and

Fig. 3. Average fork length and scale measurements of coho salmon in the western North Pacific Ocean from 1973 to 1987. Fork length (a), freshwater zone (b), the first year ocean zone (c), and the second year ocean zone (d). Open circles and broken line indicate freshwater age group one (age 1.1), solid circles and solid line indicate freshwater age group two (age 2.1), and horizontal lines indicate averages over all years for each age group. (Fig. 2 and Fig. 3 from Ogura et al. 1991).



Canada were also examined based on body weight and scale measurement data collected from 1953 to 1988 (Ishida et al.1993). A significant increase in mean age was found in Japanese and Russian stocks after 1970 when the number of Japanese chum salmon began to increase exponentially, but not in the Canadian stock. Significant decreases in mean body weight, mean scale radius, and mean width of the third-year zones of age 0.3 chum salmon also occurred in Japanese and Russian stocks after 1970. Based on the Japanese salmon research vessel data from 1972 to 1988, significant negative relationships between catch-per-unit-effort (CPUE) and mean body weight of chum salmon were observed in summer in the central North Pacific Ocean where the distribution of Japanese and Russian stocks overlapped (Fig. 4). These results suggest that density dependence is one of the possible causes for the recent changes in age and size of chum salmon in the North Pacific Ocean.

Seasonal growth patterns of chum, coho, pink and sockeye salmon (*O. nerka*) in the North Pacific Ocean were described from the biological data collected using non-selective salmon gillnets by the Japanese salmon research program (Takagi 1975; Ishida et al.1998). Maturity was determined from gonad weights (Takagi 1961; Ito et al. 1974). Seasonal change in fork length and body weight was similar between sockeye and chum salmon, and between pink and coho salmon. Seasonal change in condition factors was very similar among the four species, that is, condition factors increased in spring, peaked in summer, decreased in fall, and were lowest in winter (Fig. 5). Average growth rate in weight during maturation was significantly higher than during immaturity for sockeye, pink, and coho salmon (*t*-test, $p < 0.05$) (Ishida et al. 1998). For chum salmon, there was no significant difference in growth rate between immature and maturing fish (Ishida et al. 1998).

The potential influence of changes in sea surface temperature (SST) in the North Pacific Ocean on Japanese chum salmon adult return rates and growth rates was examined (Ishida et al. 1995). SST near the Kuril Islands (45°N, 150°E) in July ($r = -0.36$, $p < 0.05$) and SST in the central North Pacific (49°–45°N, 170°E–170°W) in winter and spring ($r = -0.61$, $p < 0.01$; $r = -0.53$, $p < 0.01$, respectively) showed significant decreasing trends from 1947 to 1988. Average return rates after the mid 1960s were higher than before the mid 1960s, when chum salmon fry were not fed prior to release at Japanese hatcheries. Return rate was negatively correlated with winter and spring SST in the central North Pacific after the mid 1960s ($r = -0.76$, $p < 0.01$; $r = -0.81$, $p < 0.01$, respectively) (Fig. 6-a). Mean body weight of age 0.3 chum salmon returning to the Ishikari River was positively correlated with the preceding three spring SST in the central North Pacific (Fig. 6-b). These results suggest that chum salmon production is enhanced in Japan by

Fig. 4. Relationship between CPUE and mean body weight of chum salmon caught by Japanese salmon research vessels in the central North Pacific in June and July from 1972 to 1988. Tan is a gillnet length unit of 50 m. *$p < 0.05$. (Fig. 6 from Ishida et al. 1993).

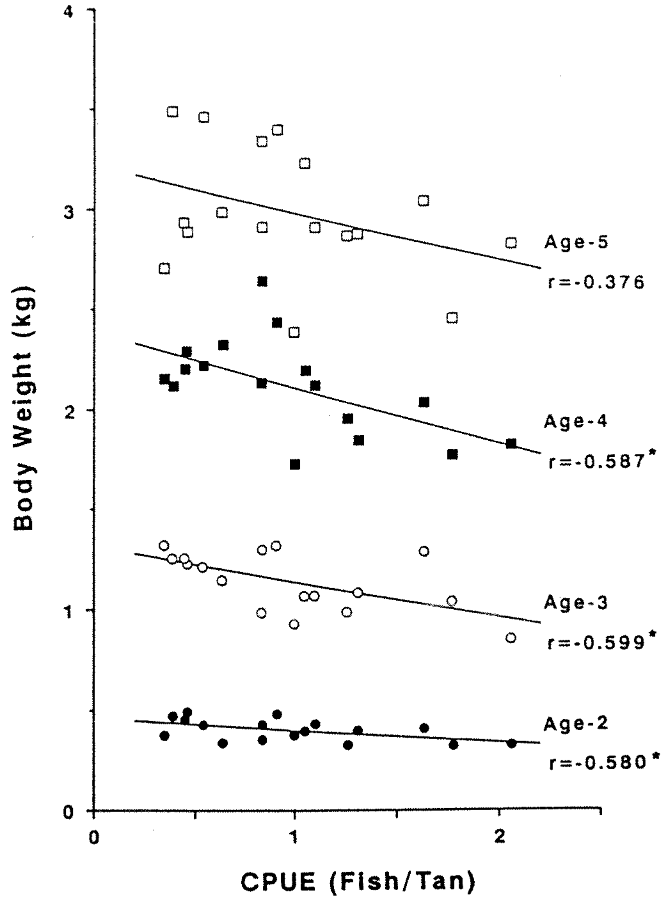


Fig. 5. Average condition factors of Pacific salmon after numbers of months at sea. Open circles, immature fish; closed circles, maturing fish. (Fig. 3 from Ishida et al. 1998).

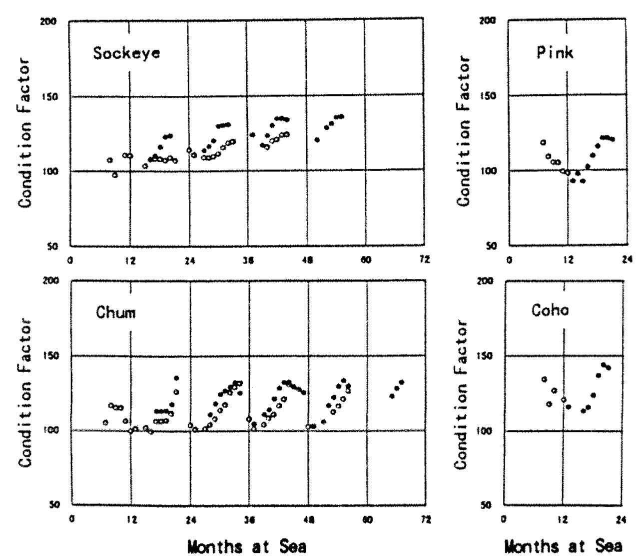
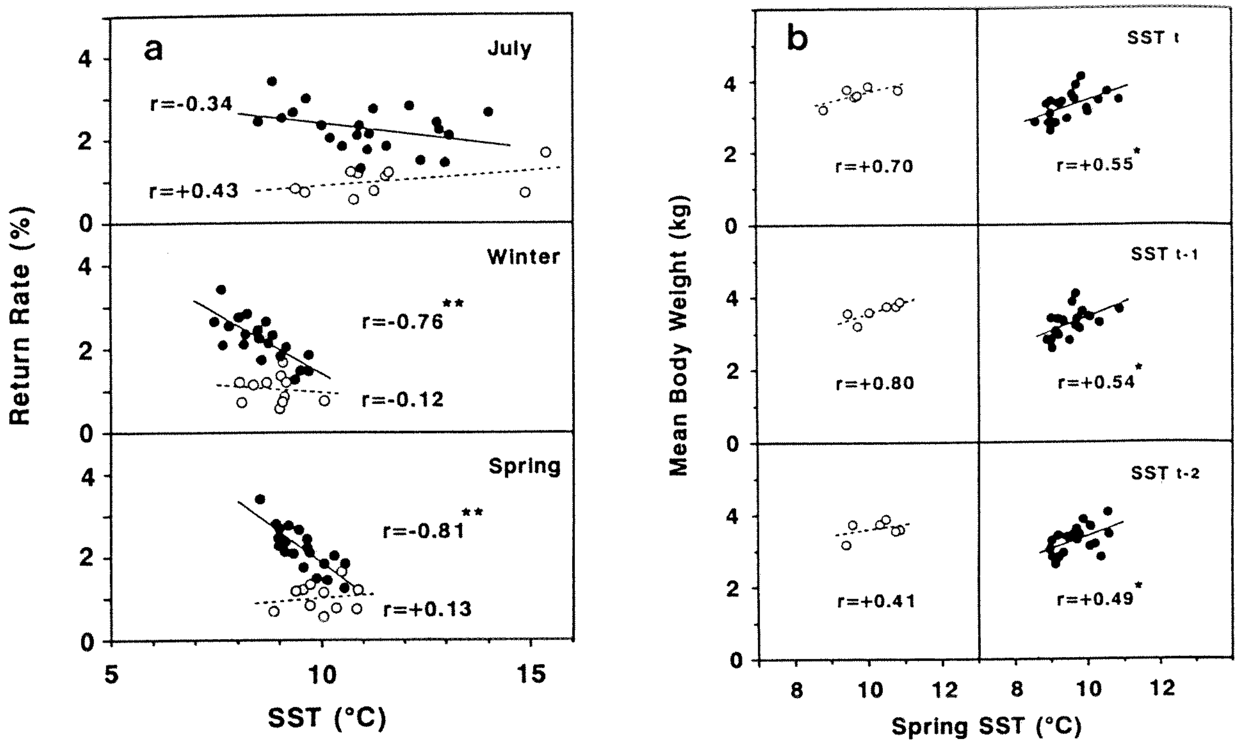


Fig. 6. Relationship between SST (near Kuril Island in July and in the central North Pacific in winter and spring) and return rates of Japanese chum salmon (*$p < 0.05$, **$p < 0.01$) (a), and relationship between the preceding three spring SSTs in the central North Pacific and mean body weight of age 0.3 chum salmon returning to the Ishikari River (b). Open circles, data for release years prior to 1966; solid circles, data for release years 1966 and subsequent year. (Fig. 3 and Fig. 5 from Ishida et al. 1995).



hatchery technology but that yields have been reduced by declining growth rates caused by decreasing SST and increasing fish density in the central North Pacific.

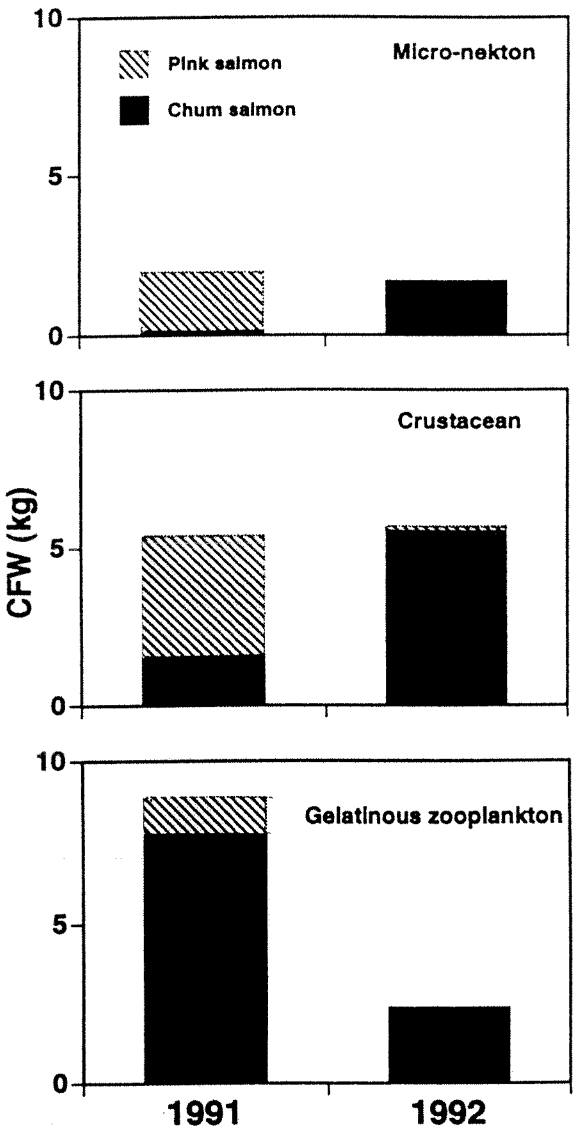
These studies suggest that salmon growth is variable and affected by intra- and inter-specific density dependent factors and also environmental factors such as SST in the North Pacific Ocean. Future objectives for salmon growth studies are: 1) examination of trade-off between increased number and decreased growth of Pacific salmon from biological and economical view points, 2) clarification of effects of reduced growth on reproduction, and 3) investigation of bioenergetics of salmon growth and environmental factors such as food conditions and SST.

Carrying Capacity Studies

The abundance and stomach contents of salmonids (*Oncorhynchus* spp.) and biomass of prey organisms were examined in the central subarctic Pacific and Bering Sea in summer of 1991 and 1992 (Tadokoro et al. 1996). Salmonids were caught by surface longline using a standardized fishing effort. Chum (*O. keta*) and pink (*O. gorbuscha*) salmon were the predominant species, representing 44% and 36% of the total catch (n = 1275) in 1991. In 1992, chum salmon composed 85% of the total catch (n = 603), but the catch of pink salmon decreased to 1% of the total catch due to the odd/even year fluctuation of pink salmon abundance in the study area. It was found that chum salmon changed their dominant diet from gelatinous zooplankton (pteropods, appendicularians, jellyfishes, chaetognaths, polychaetes and unidentified materials) in 1991, when pink salmon were abundant, to a diet of crustaceans (euphausiids, copepods, amphipods, ostracods, mysids and decapods) in 1992, when pink salmon were less abundant (Fig. 7). Local crustacean biomass (wet weight; mg/m^3) had significant negative correlation with CPUE (catch number per 30 longline) of pink salmon in 1991 (r = -0.586; p = 0.026) and that of chum salmon in 1992 (r = -0.616; p = 0.014) (Tadokoro et al. 1996). These results suggest that there is a limitation in the available prey resource for production of salmonids.

Year-to-year variations in biomass of phytoplankton (surface chlorophyll a concentration) and macrozooplankton (wet weight obtained by a North Pacific standard plankton net operation above 150 m), and abundance of pink salmon (catch per unit effort of pink salmon) from 1985 to 1994 in the subarctic North Pacific in summer were studied by Shiomoto et al. (1997). After 1989, phytoplankton biomass and pink salmon abundance showed corresponding yearly patterns, whereas the pattern shown by macrozooplankton biomass was always the inverse of that shown by

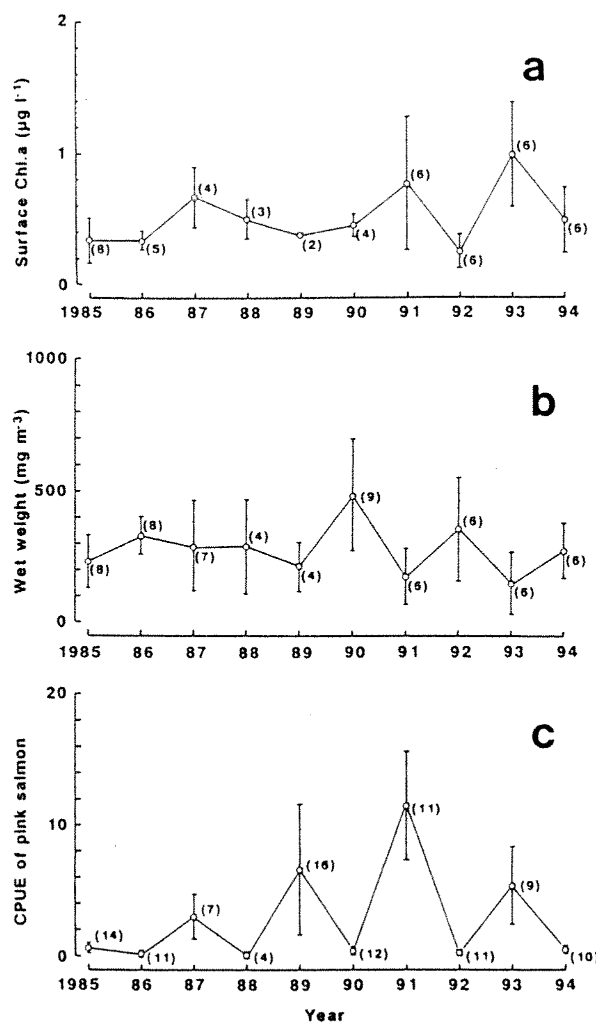
Fig. 7. Captured food weight (CFW: kg/total catch) for chum and pink salmon in 1991 and 1992. Micronekton includes squid and fish; crustaceans include euphausiids, copepods, amphipods, ostracods, mysids and decapods; and gelatinous zooplankton include pteropods, appendicularians, jellyfish, chaetognaths, polychaetes and unidentified materials. (Fig. 4 from Tadokoro et al. 1996).



phytoplankton and salmon. These patterns suggest that macrozooplankton biomass remained low when pink salmon were abundant due to the intense feeding impact of pink salmon, which in turn allowed phytoplankton biomass to remain high as a result of the lesser grazing effect of macrozooplankton. The opposite phenomenon probably occurred when pink salmon was not abundant. Prior to 1989, macrozooplankton biomass was high while phytoplankton biomass and pink salmon abundance were low (Fig. 8). Macrozooplankton biomass apparently remained high due to a lesser feeding impact of the pink salmon, and phytoplankton biomass remained low due to the intense grazing effect of macrozooplankton. These results suggest that feeding by pink salmon possibly structures summer macrozoo- and phytoplankton biomass in the subarctic North Pacific. Similar relationships among phytoplankton, macrozooplankton, and salmonid biomass were observed in the North Pacific and Bering Sea in the summers of 1992 and 1993 (Nagasawa et al. 1999).

Salmon sharks (*Lamna ditropis*) were observed to be opportunistic feeders, but occupied the highest trophic level in the food web of subarctic waters (Nagasawa 1998b). Salmonids were the major prey item for salmon sharks in the subarctic North Pacific Ocean. Although the importance of each species of Pacific salmon eaten by salmon sharks varied among regions, sockeye salmon were the most frequent prey, followed by chum, pink, coho, and chinook (*O. tshawytscha*) salmon. The conservatively estimated abundance of salmon sharks was about 2 million fish

Fig. 8. Mean yearly chlorophyll *a* concentration (a), mean wet weight of macrozooplankton (b), mean CPUE of pink salmon for each year (c). Number of samples in parentheses, error bars ±SD. (Fig. 2 from Shiomoto et al. 1997).



in 1989 (Nagasawa 1998b). Of these fish, salmon shark older than 5 years (595×10^3 fish) occurring in subarctic waters appeared to have consumed 73–146 x 10^6 salmonids (113–226 x 10^3 metric tons) from spring to autumn in 1989, which corresponded to 12.6–25.2 % of the total annual run of Pacific salmon for that year. These results suggest that predation by salmon sharks is responsible for significant mortality of Pacific salmon during their marine phase.

These studies suggest on the one hand that the salmon exercise top-down control of primary and secondary production in the North Pacific Ocean. On the other hand, linkages between climate change and salmon abundance suggest bottom-up control of salmon production in the North Pacific Ocean (Beamish and Bouillon 1993). Future issues for Japanese carrying capacity studies are: 1) confirmation of top-down and bottom-up control, 2) monitoring investigation of long-term salmon production and climate variability relating to top-down and bottom-up control, and 3) investigation of effects of top predators such as sharks, seabirds, and marine mammals on salmon production.

Forecast Studies

Estimates of high-seas abundance of salmon may be useful predictors of annual run strength. Abundance (CPUE: fish caught by gillnet with mesh sizes from 112 to 130 mm) was calculated using the data collected on board Japanese salmon research vessels in offshore waters of the North Pacific Ocean from 1972 to 1995 (Ishida and Ito 1998). These data were stratified by month, 2-degree latitude by 5-degree longitude areas (2x5 areas), species, and maturity, and related to the returns of Japanese chum salmon and Bristol Bay (Alaska) sockeye salmon. Significant correlations and high average CPUE were found in several areas. There were significant ($^*p < 0.05$, $^{**}p < 0.01$) positive correlations between CPUE of maturing chum salmon in central Bering Sea in July ($r = 0.46^*$ to 0.74^{**}) and the return of Japanese chum salmon in the same year as the samples (Fig. 9-a). The abundance of immature sockeye salmon in areas south of the Aleutian Islands ($r = 0.47^*$ to 0.65^{**}) and central Bering Sea ($r = 0.48^*$ to 0.64^*) in July was significantly and positively correlated with the returns of Bristol Bay sockeye salmon the following year (Fig. 9-b). These correlations suggest that estimates of abundance of salmon in offshore areas based on CPUE of sampling operations could be used to develop pre-season forecasts of Japanese chum salmon and Bristol Bay sockeye returns.

A significant positive relationship between the return rates of age 0.2 adults (R_2) and age 0.3 adults (R_3) was observed for chum salmon populations in Japan Sea side of Hokkaido during the 1989–1993 brood years: $R_4 = 5.891R_3$ ($r^2 = 0.969$, $p < 0.025$). The return rate of age 0.3 adults in 1997 was actually 0.97%, although it was estimated as 2.65% from the above formula and the return rate (0.45%) of age 0.2 adults in 1996. This result suggests that age 0.3 adults of the 1993 brood-year cohort might have had a lower return rate in 1997 because of some influence during the offshore migration period from autumn of 1996 to summer of 1997, despite their high return rate at age 0.2 (Kaeriyama et al. 1998).

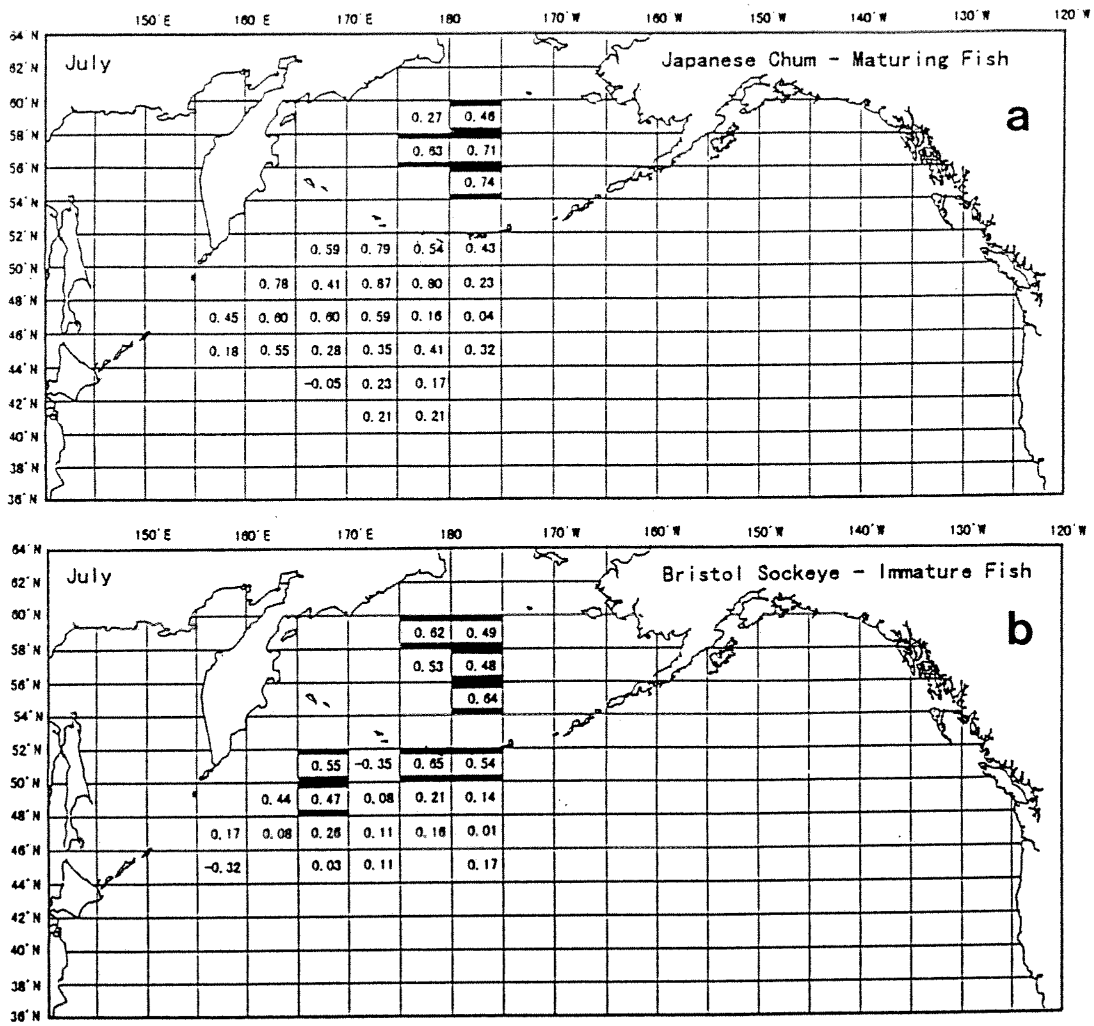
Relatively high positive correlation coefficients were found between survival rates of Russian pink salmon and the SST in the Okhotsk Sea and the waters off the East Kamchatka in August of years of fry emigration. The survival rates of pink salmon from Alaska were also positively related to SSTs in the waters along the West Coast of North America in August. These seasons correspond to the period when mortality rate is the highest in the ocean life of pink salmon. These results suggest that survival rates of pink salmon are affected by SST changes at a local level (Azumaya et al. 1998).

The forecast studies suggest that several possible methods may be useful in the North Pacific Ocean. Reliable salmon forecasts are one of the main objectives of salmon research; they are needed not only for salmon harvest management and conservation of stocks, but also for the efficient operation of salmon fisheries and processing industries. Future issues for forecast studies are: 1) inclusion of additional biological characters such as age composition and body size in forecasts, 2) cost and benefit analysis of forecast research in offshore waters, and 3) development of quick and accurate stock assessment tools, e.g. by surface trawl and/or acoustic surveys.

Winter Salmon Studies

Oceanographic and biological data collected in the trans-Pacific survey during early winter (1992), mid-winter (1996) and late winter (1998) were analyzed (Ueno et al. 1999). The seasonal changes of the distribution of sockeye, chum (except for juvenile), and coho salmon strongly indicated that they migrate eastwards from the western or central North Pacific to the eastern North Pacific in the winter. Strong eastward water transport in the upper ocean associated with the storms in the western North Pacific may accelerate the eastward migration of these salmonids. A high density of juvenile chum and pink salmon was observed in the western North Pacific Ocean in mid-winter. Sea surface temperature at 8°C indicated the southern boundary of salmon distribution in the North Pacific Ocean (Fig. 10). These results suggest that only subarctic waters are suitable for wintering salmon. Low temperatures in the subarctic waters seem to decrease the metabolic rate. The northern boundary of salmon distribution corresponded with about 4°C at sea surface in the North Pacific Ocean in

Fig. 9. Correlation coefficients between density (CPUE) of maturing chum salmon in 2° x 5° areas in July of year t and return of Japanese chum salmon in year t (a), and correlation coefficients between density (CPUE) of immature sockeye salmon in 2° x 5° areas in July of year t and return of Bristol Bay sockeye salmon in year t+1 (b). Shaded areas indicate higher average CPUE and significant correlation coefficients ($p < 0.05$). (Fig. 2 and Fig. 3 from Ishida and Ito 1998).



late winter. However, a few chinook salmon occurred in waters north of this boundary, where the SSTs ranged from 1°C to 4°C.

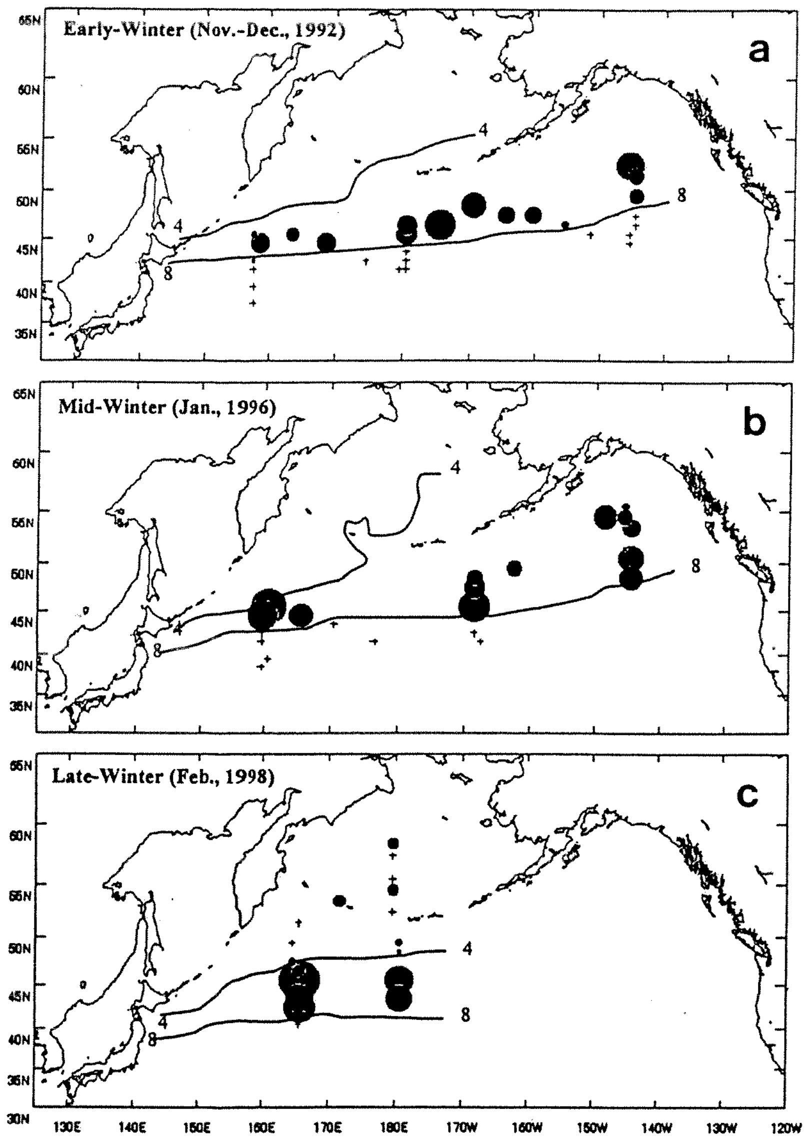
The use of measurements of total lipid content and lipid classes in the white muscle and liver of pink and chum salmon was examined for their potential to describe trophic condition during their ocean life (Azuma et al. 1998; Nomura et al. 1999). In winter, the total lipid contents of chum and pink salmon were extremely low and the total lipid content of the white muscle of pink salmon varied by capture location. The total lipid content in the white muscle of immature chum salmon was significantly lower than in maturing chum salmon in spring. The total lipid of the white muscle in maturing pink salmon in the Japan Sea was significantly higher than in pink salmon in the North Pacific Ocean. In summer, the total lipid content of the white muscle increased in both species, but a significant difference in the total lipid content was observed according to the capture locations. The extremely low lipid contents in winter suggest that chum and pink salmon are confronted with great energetic challenge during this season.

The winter salmon studies suggest that winter is one of the critical periods for salmon population in the North Pacific Ocean. Future issues for the winter salmon studies are: 1) investigation of migration routes and environment conditions of Pacific salmon using archival tag data in winter, and 2) examination of effect of possible food shortage on salmon survival and growth in winter.

CONCLUSIONS

The eight year ocean salmon research by Japanese scientists in cooperation with scientists of Canada, the Russian Federation and the United States of America have began to solve many questions identified by the

Fig. 10. Distribution of salmon abundance (CPUE) and sea surface temperature in early winter (November–December, 1992) (a), mid winter (January 1996) (b), and late winter (February 1998) (c) in the North Pacific Ocean. (Fig. 2 from Ueno et al. 1999).



NPAFC Science Plan, and revealed new issues for future salmon research. In order to promote the future ocean salmon research, we need to concentrate our effort on specific waters, such as the Okhotsk Sea and Gulf of Alaska for juvenile salmon studies, and the Bering Sea for salmon growth, carrying capacity, and forecast studies. Winter salmon studies are also needed to clarify the critical period for the salmon ocean life. These issues should be incorporated into a revised NPAFC Science Plan scheduled in 2000 and investigated by the scientists under the cooperation of Pacific Rim countries.

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