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Distribution and CPUE Trends in Pacific Salmon, Especially Sockeye Salmon in the Bering Sea and Adjacent Waters from 1972 to the mid 2000s

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Abstract: We present the mean CPUE distributions of five species of Pacific salmon in the Bering Sea and adjacent waters, based on long-term data from Japanese research-gillnet operations, 1972–2002. Many populations of three abundant Pacific salmon species (pink, chum, and sockeye salmon), have feeding migrations in the Bering Sea. There are two distinct patterns in the fluctuations in CPUE of major North Pacific salmon species in the Bering Sea. The CPUEs of pink and Chinook salmon increased after 1988 and remained high to 2005. The CPUEs of sockeye and chum salmon were low prior to 1977, peaked in 1980, declined until 1989, and then increased again until 2005. The trends in CPUE of sockeye and chum salmon seem to coincide with fluctuations in Bering Sea sea surface temperatures (SST) with higher densities of sockeye and chum salmon in the Bering Sea during warm periods and lower densities during cool periods, especially in sockeye. These increases and decreases in CPUE seem to coincide with the hypothesized regime shifts in 1977 and 1989. We also discuss the effects of the semi-decadal fluctuations in the Bering Sea SST, and related fluctuations in sockeye salmon abundance.

Keywords: horizontal distribution, CPUE trends, SST, Bering Sea, sockeye salmon

INTRODUCTION

Japanese high-seas salmon research has been conducted since 1952. Until recently, we used research driftnets as the standard gear for most salmon research programs (Takagi 1975). We have many data from these surveys that were conducted during the months of June, July and August (Ishida and Ogura 1992). The Bering-Aleutian Salmon International Surveys (BASIS) began in 2002, and was designed to cover both the high seas and waters within the 200 naut. mi. limit of the USA and Russia in the Bering Sea using a surface trawl net. Today the surface trawl net is the semi-standard fishing gear for salmon research in the North Pacific Ocean. Although, the time series data obtained from trawl net surveys are not yet adequate, Japanese gillnet surveys will likely decrease in the near future because of the high cost of supporting both trawl and gillnet surveys for salmon. Studies on the horizontal distribution of major Pacific salmon species using data from Japanese research gillnet surveys have been reviewed (Godfrey et al. 1975; French et al. 1976; Neave et al. 1976; Major et al. 1978; Takagi et al. 1981). However, the results of Japanese research cruises conducted after 1972 are not well described in these articles. In this paper, we present a retrospective analysis of driftnet data collected from 1972 to 2008, especially on the distribution of each species, classified by age. We think mean CPUE horizontal distribution patterns by species, by month, and by ocean age will be a helpful tool for further understanding the nature of Pacific salmon.

After the late 1980s many researchers described the synchrony observed between fish stock fluctuations and climate fluctuations (e.g., Kawasaki et al. 1991). Beamish and Bouillon (1993) introduced the relationships between Pacific salmon catches and decadal-scale climate trends. The Bering Sea is a major feeding area for the many economically important salmon stocks of both Alaskan and Asian origin. While there is coherence in long-term trends in climate change effects on salmon production at basin scales, analysis of CPUE trends in this area may further contribute to our knowledge of relationships between salmon population abundance and climate change.

The objectives of this paper were to 1) map CPUE in relation to sea surface temperature (SST) by age and month, 2) compare temporal trends in CPUE by species, 3) compare

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temporal trends in CPUE and SST, 4) compare CPUE and fork length of sockeye salmon (*Oncorhynchus nerka*) to the Bristol Bay sockeye salmon catch, and 5) compare sockeye salmon fork length to walleye pollock (*Theragra chalcogramma*) abundance.

MATERIAL AND METHODS

We analyzed catch data obtained by Japanese research-gillnet operations (Takagi 1975) for distribution patterns in mean CPUE from 1972 to 2002, because Japanese research-gillnet operations have decreased since 2002. To describe the distributions, we stratified the whole area by 2-degree latitude and 5-degree longitude grid sections, following Azumaya and Ishida (2000). We calculated the long-term mean density of each species by age group and month. We used the mean CPUE for each month for the density index. The mean CPUE in each grid was calculated as follows:

CPUE = total catch in number / total effort (in units of 30 tans of research-gillnet).

Mean monthly SST data were provided for 2° × 2° grids from 1972 to 2002 by the Japan Meteorological Agency. The proportions of maturing and immature fish in each grid were calculated based on maturity definitions that are based on gonad weight (Takagi 1961; Ishida et al. 1961; Ito et al. 1974). We estimated fish age by scale observations following Ito and Ishida (1998). In this paper we used the "European" system for age designation, in which the winters in fresh water after hatching and the winters in sea water are identified and separated by a period. Because estimated freshwater ages of sockeye and Chinook salmon (*O. tshawytscha*) varied by reader, we did not determine freshwater ages of sockeye and Chinook but we did use ocean ages. In these cases, an x.2 fish has spent an unknown number of winters in fresh water, and two winters in sea water.

Although the main research areas of Japanese research-gillnet operations have been restricted since 1992, we have been able to maintain the summer research operations in the Bering Sea. Therefore, we analyzed the mean July CPUE in the Bering Sea from 1972 to 2008 to obtain the long-term density trends in salmon in the Bering Sea. To detect the trends in decadal fluctuation patterns or longer-term trends, we used five-year running means (5YRM) for both salmon CPUE and SST. A five-year running mean is an effective filter to exclude annual fluctuations.

The Bristol Bay sockeye salmon stock is a large stock in the North Pacific. We used commercial catch statistics for Bristol Bay as an index of sockeye salmon abundance. We compiled this catch data from INPFC Statistics Year Books, NPAFC Statistics Year Books, and from Eggers (2004) for 1993. We also calculated the annual mean fork length (FL) of sockeye salmon of each ocean age caught by Japanese research-gillnet operations in July. The mean FL in each year was calculated as the arithmetic average of all samples from Japanese research-gillnet operations in the Bering Sea in July. We also calculated the growth rate of sockeye salmon between age x.1 and x.2 as: growth rate of t year = average fork length of age x.2 sockeye salmon in July in t year – average fork length of age x.1 sockeye salmon in July in t -1 year.

RESULTS

Horizontal Distribution of Sockeye Salmon Mean CPUE

Most age x.1 sockeye salmon were immature. In June, age x.1 sockeye salmon were mainly distributed in the North Pacific Ocean where SST ranged from 5–8°C; a few were distributed in the Bering Sea, but few in areas < 5°C (Fig. 1). In July, some portion of immature age x.1 sockeye salmon entered the Bering Sea, but the rest remained in the North Pacific Ocean either along the Aleutian archipelago, or in the Gulf of Alaska. The SST over most of the distribution area ranged from 7–10°C, but ranged from 9–12°C in the Gulf of Alaska. In August, most age x.1 sockeye salmon appeared along the Aleutian archipelago and the eastern coast of Kamchatka. The catch of age x.1 sockeye salmon occurred at temperatures < 11°C.

In June, catch of age x.2 sockeye salmon mainly occurred in waters ranging from 5–8° C (Fig. 2). Around the eastern part of the Aleutian archipelago and the Alaska Peninsula, especially in the eastern Bering Sea near Bristol Bay, CPUE of maturing sockeye salmon was high. In other waters, the proportion of maturing fish was < 50%. In July, age x.2 sockeye salmon CPUE was high around the Alaska Peninsula and the eastern portion of the Gulf of Alaska. The proportion of maturing fish was also high around Kamchatka, but CPUE was not high. The CPUE of immature age x.2 sockeye salmon was high in the North Pacific Ocean along the Aleutian archipelago. The catch of immature age x.2 sockeye salmon occurred in waters at 7–9°C, and the catch of maturing age x.2 sockeye salmon in waters at 7–12°C. In August, a small catch of maturing age x.2 sockeye salmon occurred around Kamchatka, but they were not found in the other waters. A catch of immature x.2 sockeye salmon occurred in both the Bering Sea and North Pacific Ocean at 8–11°C.

Most age x.3 sockeye salmon were maturing fish. In June, the catch of age x.3 sockeye salmon occurred in waters at 3–9°C, and CPUE was high around the Alaska Peninsula and along the eastern Aleutian archipelago (Fig. 3). In July, maturing age x.3 sockeye salmon occurred in waters at 7–12°C, with two high CPUE areas, one around the Alaska Peninsula, and another near Kamchatka. In August, a few maturing sockeye salmon were distributed around Kamchatka, the Aleutian archipelago, and northern waters of the Bering Sea, but none occurred in the central portion of the Bering Sea.

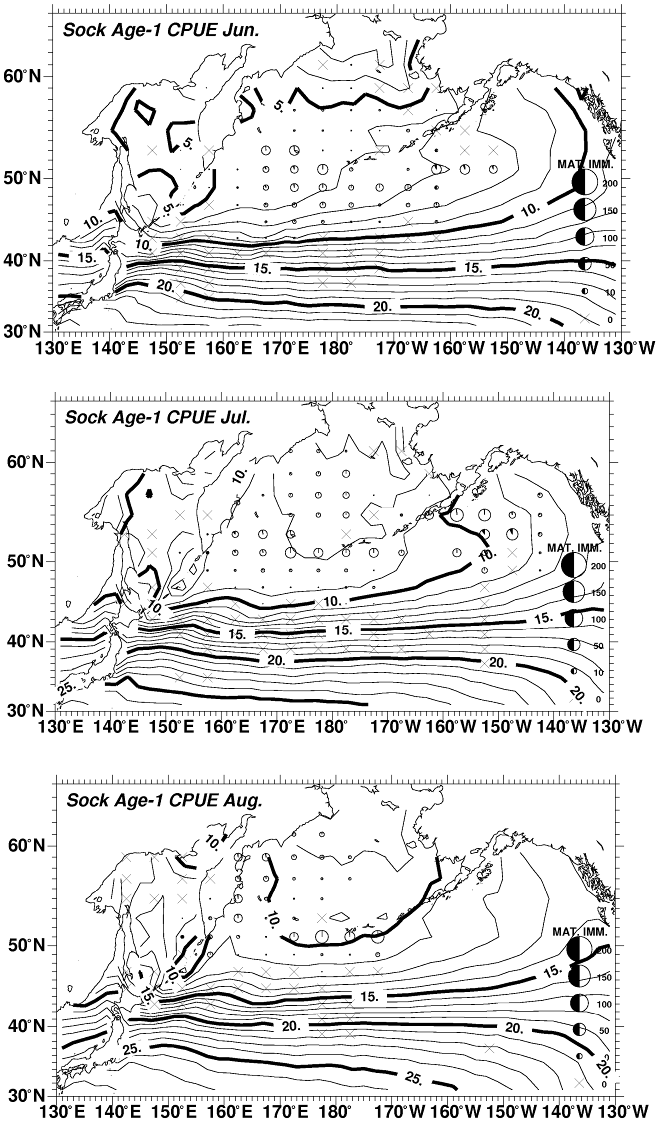

Fig. 1. Monthly ocean distribution of ocean age .1 (x.1) sockeye salmon in the North Pacific Ocean. Circle size indicates catch per unit effort (CPUE). Solid symbols indicate maturing fish (MAT), open symbols indicate immature fish (IMM), X indicates 0 CPUE. Lines indicate Sea Surface Temperature (SST).

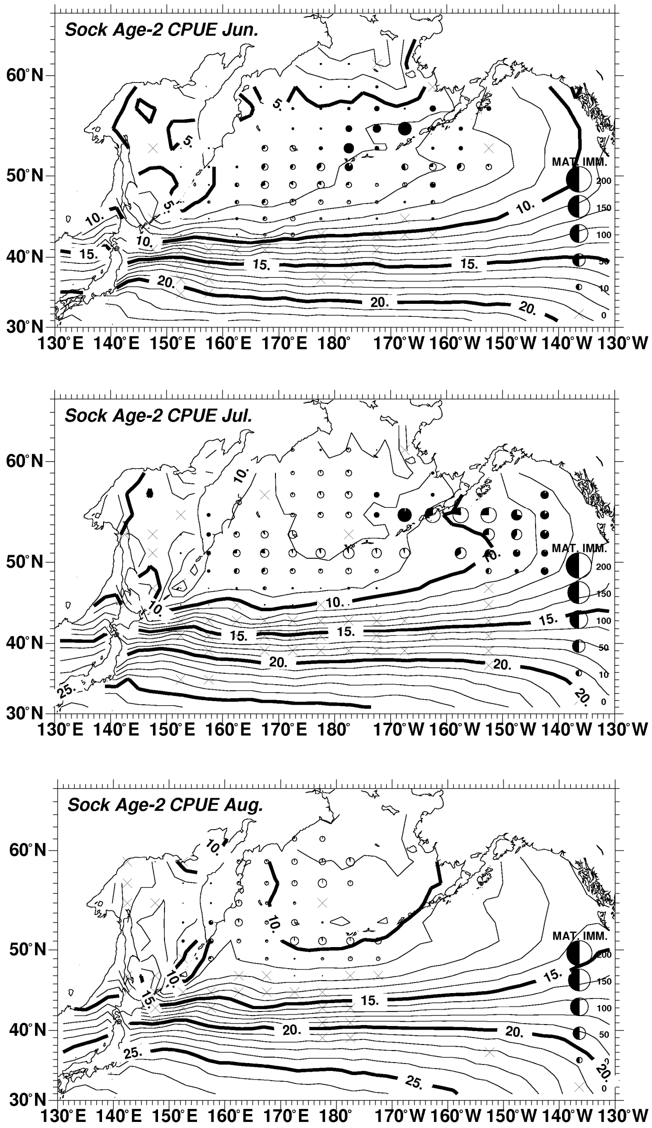

Fig. 2. Monthly ocean distribution of age x.2 sockeye salmon in the North Pacific Ocean. Symbols as in Fig. 1.

Horizontal Distribution of Chum Salmon Mean CPUE

Most age 0.1 chum salmon (*O. keta*) were immature. In June, the distribution of age 0.1 chum salmon occurred in waters at 5–10°C, but did not occur in the Bering Sea (Fig.4). In July, the catch of age 0.1 chum salmon occurred broadly in waters at 7–12°C. High densities were recorded in the central part of the Bering Sea and the central North Pacific between 170°E–170°W, but few occurred in the eastern Bering Sea. In August, the catch of age 0.1 chum salmon mainly occurred in waters < 12°C. High CPUEs occurred in the central and northeastern Bering Sea.

In June, the catch of age 0.2 chum salmon mainly occurred in waters at 6–10°C (Fig. 5). Small catches also occurred in waters at 3–6°C including the Bering Sea, and 10–13°C. No catch occurred in the northwestern portion of the Gulf of Alaska. The proportion of maturing fish was < 25 % in all waters. In July, catches of age 0.2 chum salmon occurred broadly in waters at 7–15°C. High CPUEs occurred in the central Bering Sea at 7–8°C, and in the Gulf of Alaska at 10–12°C. Around Kamchatka, the proportion of maturing fish was higher than in other waters. In August, catches of age 0.2 chum salmon occurred in waters < 15°C. High CPUEs occurred in the Bering Sea.

In June, catches of age 0.3 chum salmon occurred in waters < 17°C. The catches of immature age 0.3 chum salmon only occurred in waters at 5–9°C (Fig. 6). The proportion of maturing chum was higher in coastal areas on both sides

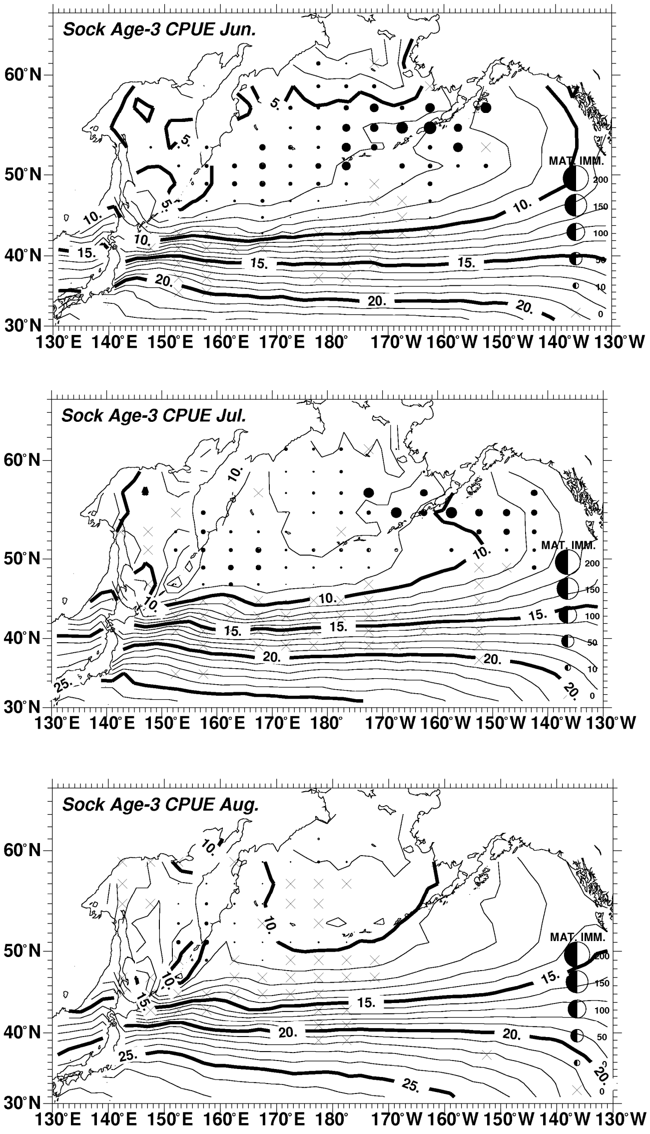

Fig. 3. Monthly ocean distribution of age x.3 sockeye salmon in the North Pacific Ocean. Symbols as in Fig. 1.

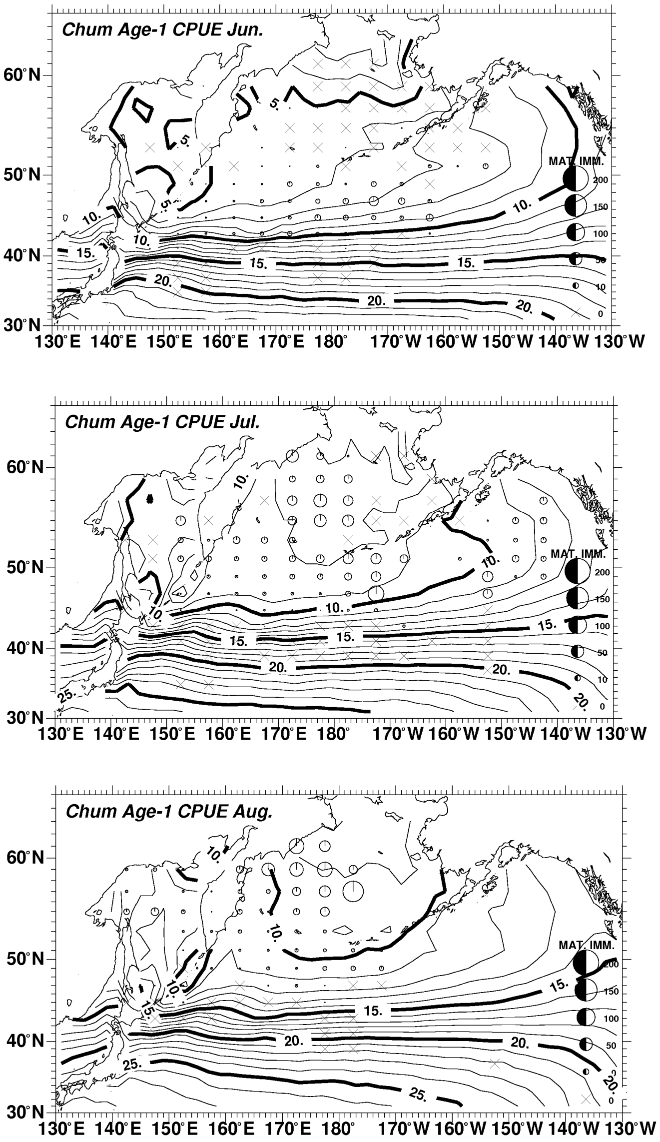

Fig. 4. Monthly ocean distribution of age 0.1 chum salmon in the North Pacific Ocean. Symbols as in Fig. 1.

of the North Pacific Ocean than in offshore waters. In July catch of age 0.3 chum salmon occurred in waters < 13°C. The two areas of high CPUE were around Kamchatka and in the Bering Sea. The proportion of maturing chum salmon was high in the waters around Kamchatka and near Bristol Bay. In August, the catch of age 0.3 chum salmon occurred in waters < 14°C. The proportion of maturing fish was lower than that in July.

Most age 0.4 chum salmon captured were maturing. In June, the catch of age 0.4 chum salmon occurred in waters at 3–17°C (Fig.7). High CPUEs occurred near Bristol Bay, the central Bering Sea, and around Kamchatka. In July, catches of age 0.4 chum salmon occurred in the Bering Sea in waters at 7–9°C; CPUE was low elsewhere. In August, catches of age 0.4 chum mainly occurred in waters at 10–12°C in the central North Pacific Ocean between 160°W and 180°; few were captured elsewhere.

Horizontal Distribution of Pink Salmon Mean CPUE

Because they have a two-year life span, all pink salmon (*O. gorbuscha*) caught in research-gillnet operations were maturing. In June, catches of pink salmon occurred broadly in waters at 3–17°C, and high CPUEs occurred in waters of the western North Pacific at 5–10°C (Fig.8). In July, two areas of high CPUE distribution occurred, one in the western North Pacific, especially around Kamchatka at 8–11°C, and another in the central Bering Sea at 6–7°C. In August, catches of pink salmon only occurred in waters off the Asian coast.

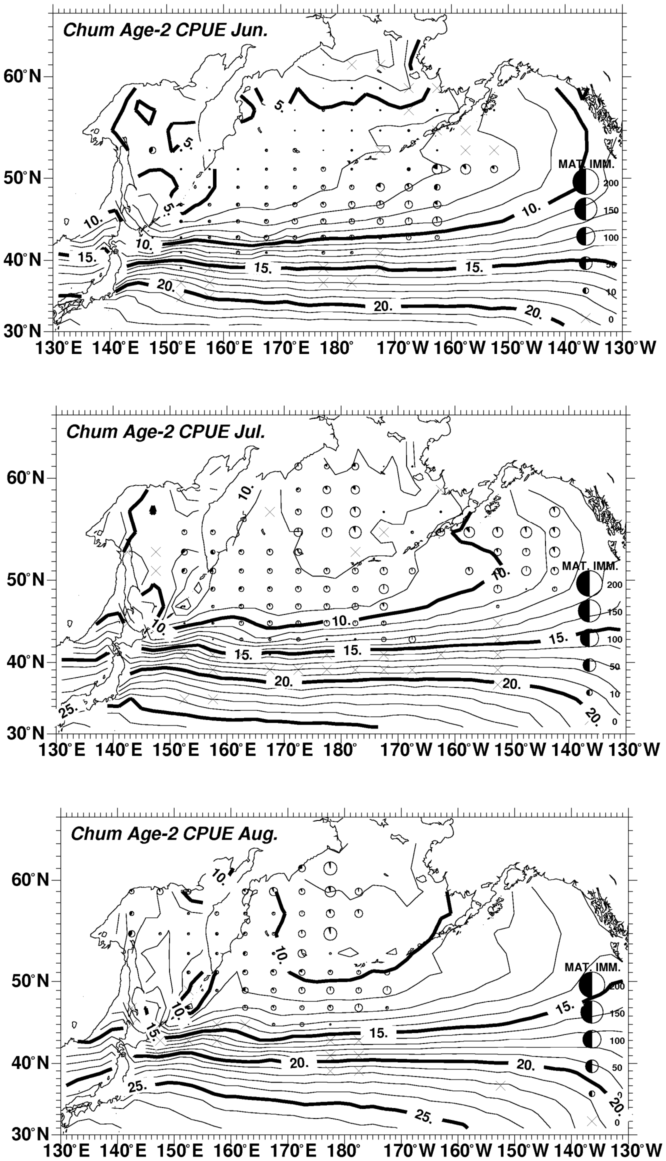

Fig. 5. Monthly ocean distribution of age 0.2 chum salmon in the North Pacific Ocean. Symbols as in Fig. 1.

Horizontal Distribution of Coho Salmon Mean CPUE

All coho salmon (*O. kisutch*) caught by research-gillnet operations were maturing, because their growth period includes one winter in the sea. In June, catches of coho salmon occurred in waters at 5–13°C. The high CPUEs occurred at 7–11°C in the central North Pacific between 160ºE and 160ºW. CPUEs were low in other waters. Few catches occurred in the Bering Sea. In July, catches of coho salmon occurred at 7–16°C, however, coho salmon were rare in research-gillnet samples. In August, catches of coho salmon occurred in waters at 8–14°C. Coho salmon CPUEs around Kamchatka were higher than those in the central North Pacific.

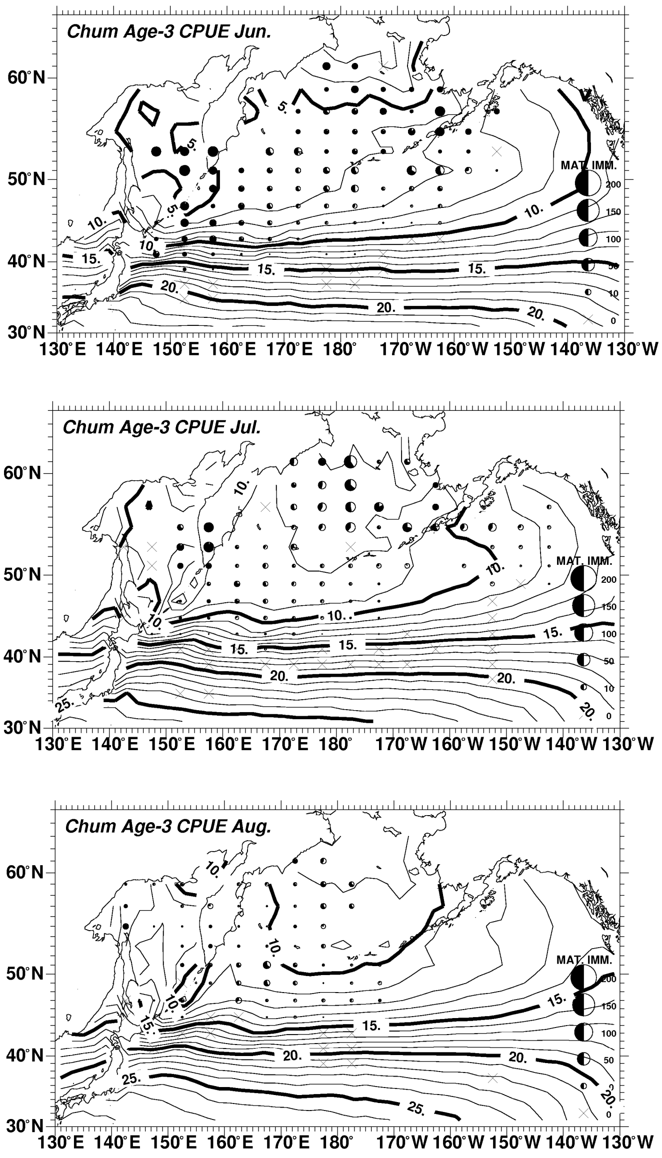

Fig. 6. Monthly ocean distribution of age 0.3 chum salmon in the North Pacific Ocean. Symbols as in Fig. 1.

Horizontal Distribution of Chinook Salmon Mean CPUE

In June, the catch of age x.1 Chinook salmon occurred in waters at 3–7°C in the Bering Sea, and 6–9°C in the central North Pacific (Fig. 10). In July, the catch of age x.1 Chinook salmon occurred in waters at 7–11°C. In August, catches of age x.1 Chinook salmon occurred in waters < 13°C.

In June, catch of age x.2 Chinook salmon occurred widely at temperatures > 2–10°C, including the North Pacific, Bering Sea, Okhotsk Sea, and Gulf of Alaska (Fig. 11). In July, the catch of age x.2 Chinook salmon occurred widely at 7–12°C. In August, the catch of age x.2 Chinook salmon occurred in waters < 13°C.

In June, catches of age x.3 Chinook salmon occurred

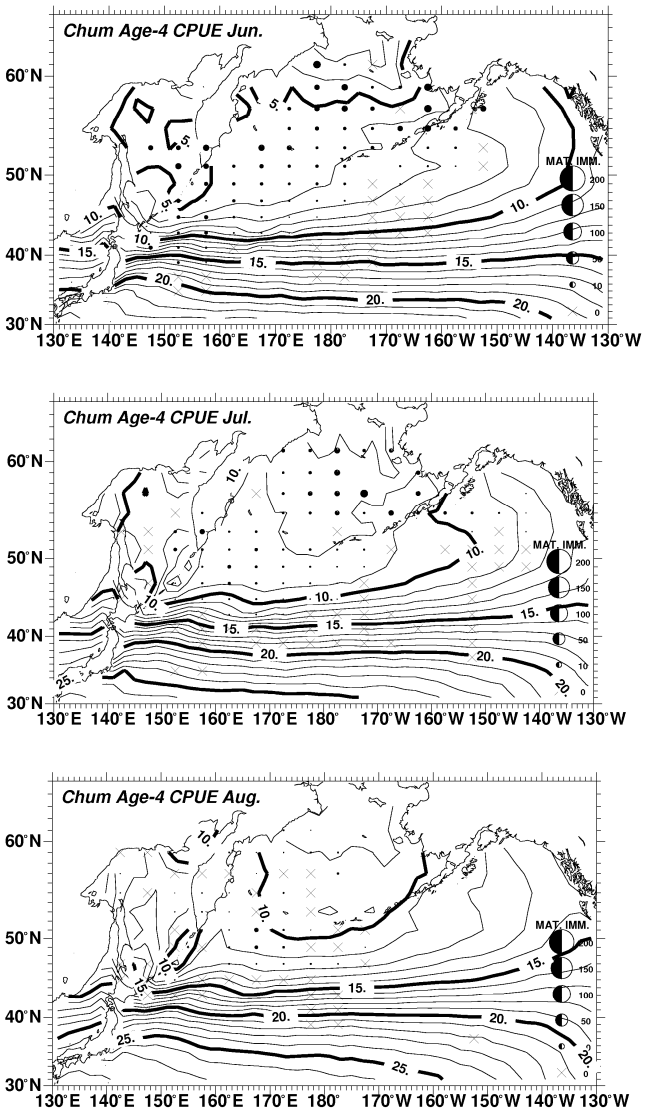

Fig. 7. Monthly ocean distribution of age 0.4 chum salmon in the North Pacific Ocean. Symbols as in Fig. 1.

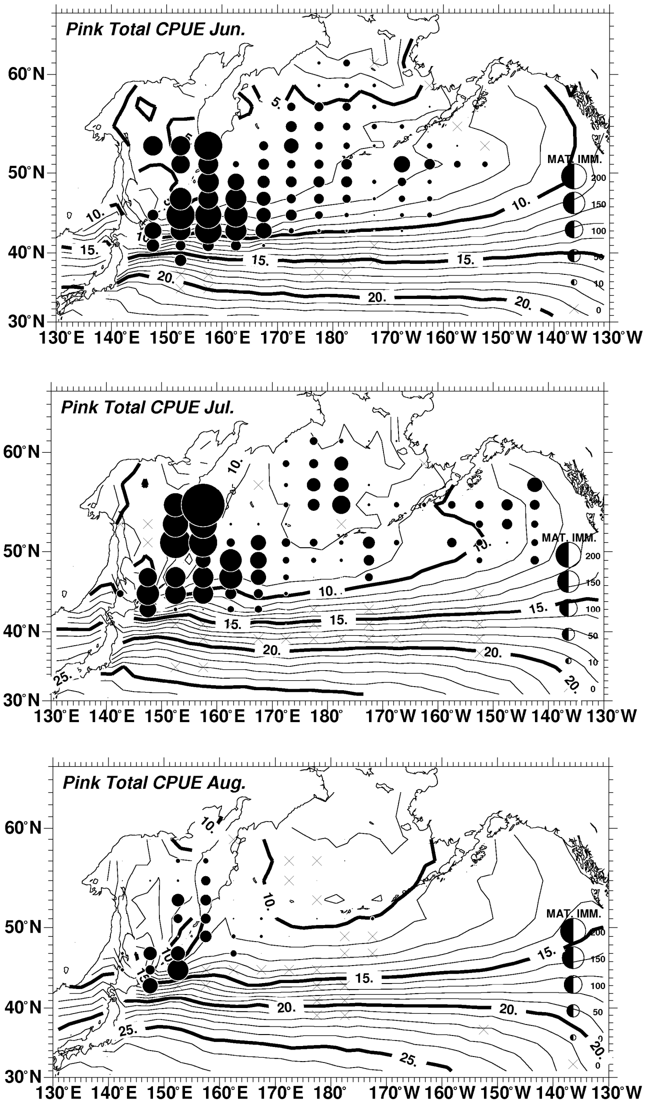

Fig. 8. Monthly ocean distribution of age 0.1 pink salmon in the North Pacific Ocean. Symbols as in Fig. 1.

in waters at 3–10°C in the Bering Sea, the North Pacific, and the Sea of Okhotsk (Fig. 12). In July, age x.3 Chinook salmon occurred widely at temperatures < 12°C. In August, catches of age x.3 Chinook salmon were small, but occurred in waters < 12°C.

The catch records of age x.4 Chinook salmon in research gillnets were few. In June the catch of age x.4 Chinook occurred in waters at 4–8°C (Fig. 14). In July the highest catch of age x.4 Chinook salmon occurred at 7–8°C in the Bering Sea, and at 9–10ºC in the western North Pacific. In August, catches of age x.4 Chinook salmon were not recorded anywhere.

CPUE Fluctuation of Salmon in the Bering Sea

There were two patterns of CPUE fluctuation, one for sockeye and chum salmon (Fig 14A), the other for pink and Chinook salmon (Fig. 14B). Until 1977, the CPUEs for sockeye and chum salmon were low; they then became high by 1980, became low again by 1989, and then became high until the present. The CPUEs of pink and Chinook salmon became high and remained so after 1988; prior to 1988 CPUEs were consistently low (Fig. 14B). Among these four species, the 5-year running mean (5YRM) CPUE trends in sockeye and chum salmon were similar to the 5YRM SST fluctuation, especially in sockeye (Fig. 15). It seems that sockeye salmon density was higher in warm periods than in cool periods in the Bering Sea. There was positive linear correlation between 5YRM SST and 5YRM CPUE of sockeye salmon (Fig. 16).

After 1980, commercial catches of the sockeye salmon in Bristol Bay have remained at high levels (Fig. 17). The five-year running mean of sockeye commercial catches after 1980 had two modes, one was in 1983, and the other was in

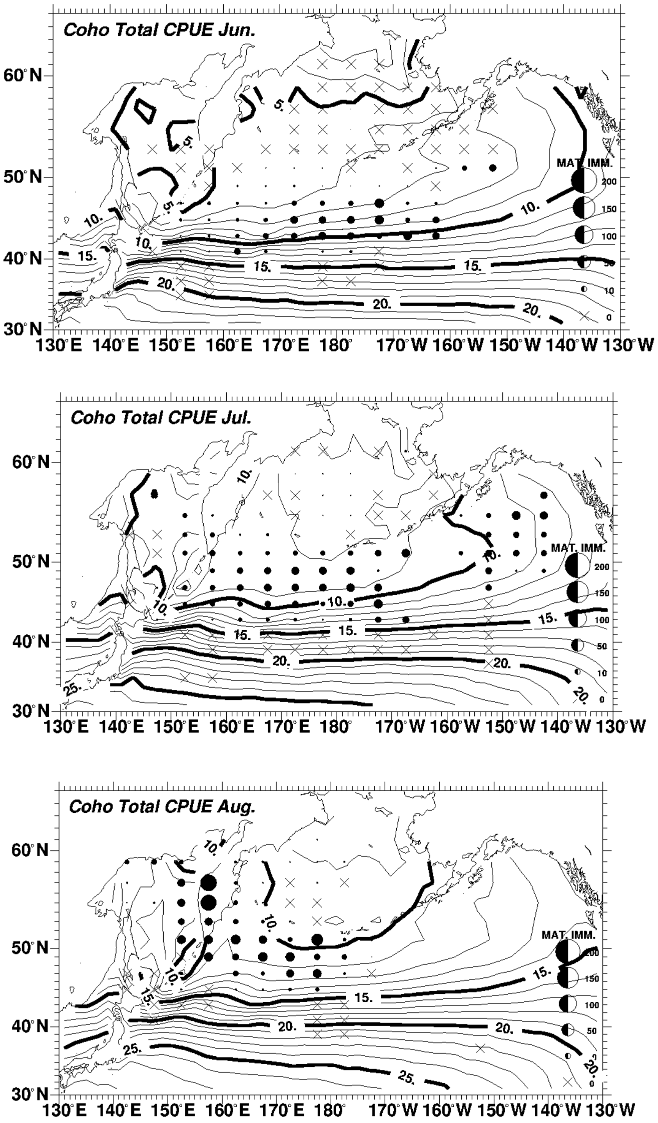

Fig. 9. Monthly ocean distribution of age x.1 coho salmon in the North Pacific Ocean. Symbols as in Fig. 1.

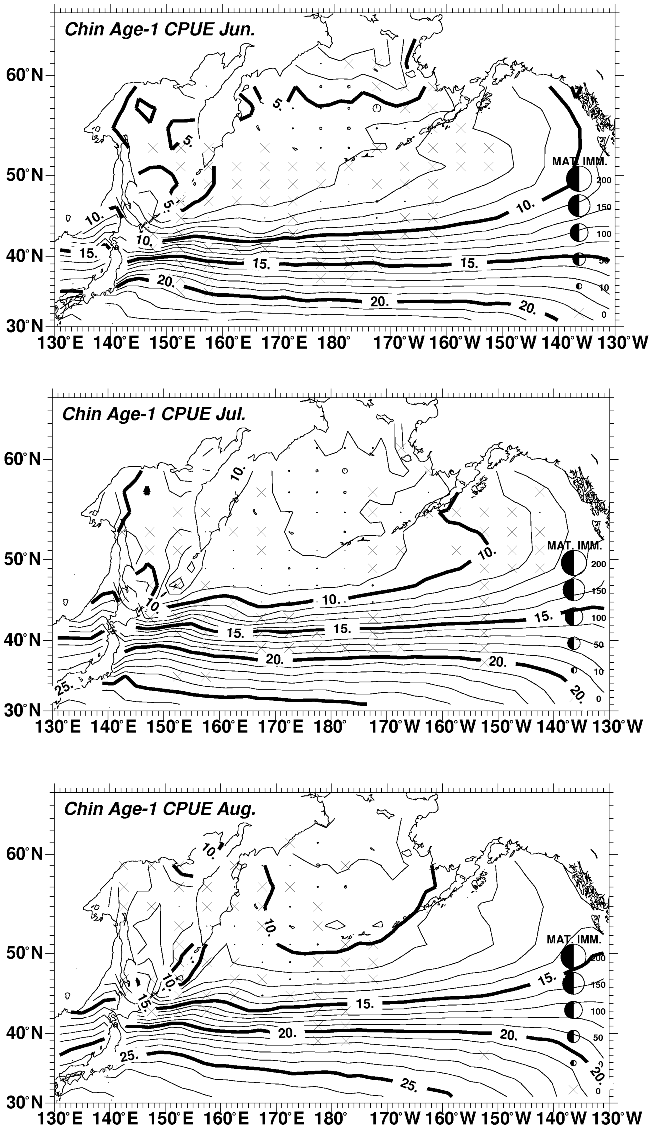

Fig. 10. Monthly ocean distribution of age x.1 Chinook salmon in the North Pacific Ocean. Symbols as in Fig. 1.

1994. The 5YRM CPUE of sockeye salmon by Japanese research-gillnet operations also had two modes: one was in 1981 and the other was in 1995. The high and low fluctuation patterns of both index values were very similar.

Size Trends of Sockeye Salmon Caught in the Bering Sea

The mean FL of age x.1 sockeye salmon in the Bering Sea was low between 1972 and 1976 (excluding 1973 (Fig. 18)). After 1977, the mean FL became larger (exceeding 340 mm) until 1984. In 1986, the mean FL of age x.1 sockeye salmon was the smallest (about 290 mm), and then increased up to 1994. After 1995, the mean FL of age 0.1 sockeye salmon fluctuated between 319–348 mm. The trends in mean FL of age x.2 and older sockeye salmon were opposite to the trend in age 0.1 fish. The mean FL of age 0.2 sockeye salmon was largest in 1976, and exceeded 510 mm between 1986 and 1990. The trend in mean FL of age x.3 sockeye salmon was similar to that of age x.2. The calculated growth between age x.1 and x.2 were large from 1974–1977 and 1986–1989. During these periods, mean FL of age x.1 sockeye salmon was small.

Although the mean FL of age x.1 sockeye salmon fluctuated annually, 5YRM showed clear oscillations. The oscillation pattern of the 5YRM of FL of age x.1 sockeye salmon showed two peaks, one in 1978–1983 and the other in 1992–1995 (Fig. 19). The peaks and valleys of this oscillation pattern were similar to the trends in 5YRM commercial catches of Bristol Bay sockeye salmon.

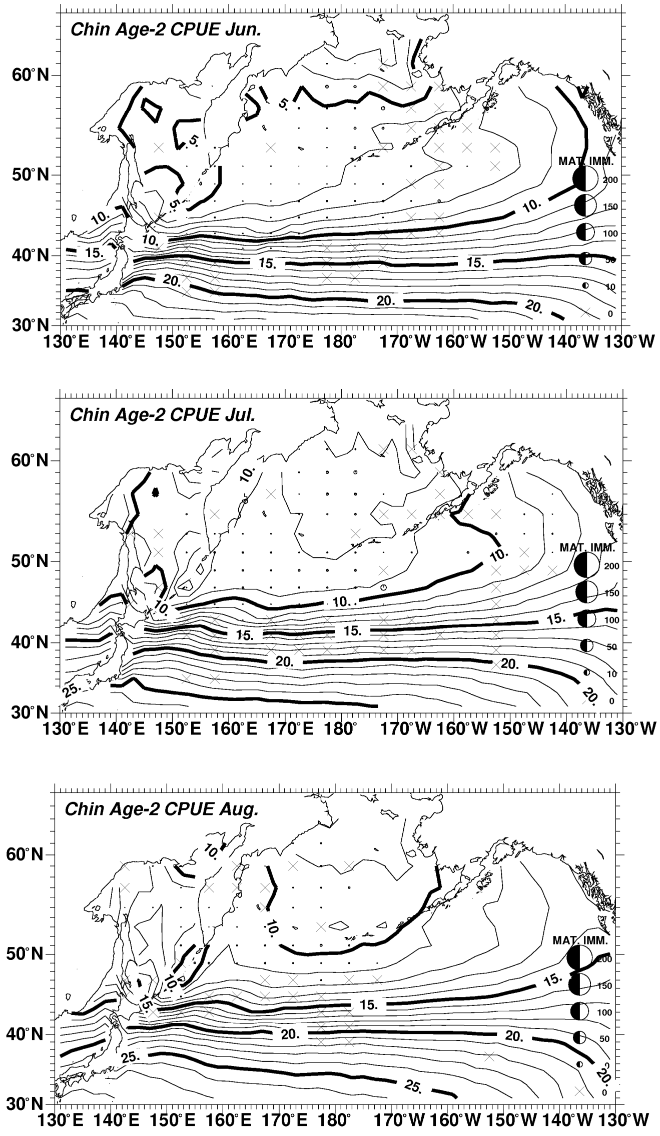

Fig. 11. Monthly ocean distribution of age x.2 Chinook salmon in the North Pacific Ocean. Symbols as in Fig. 1.

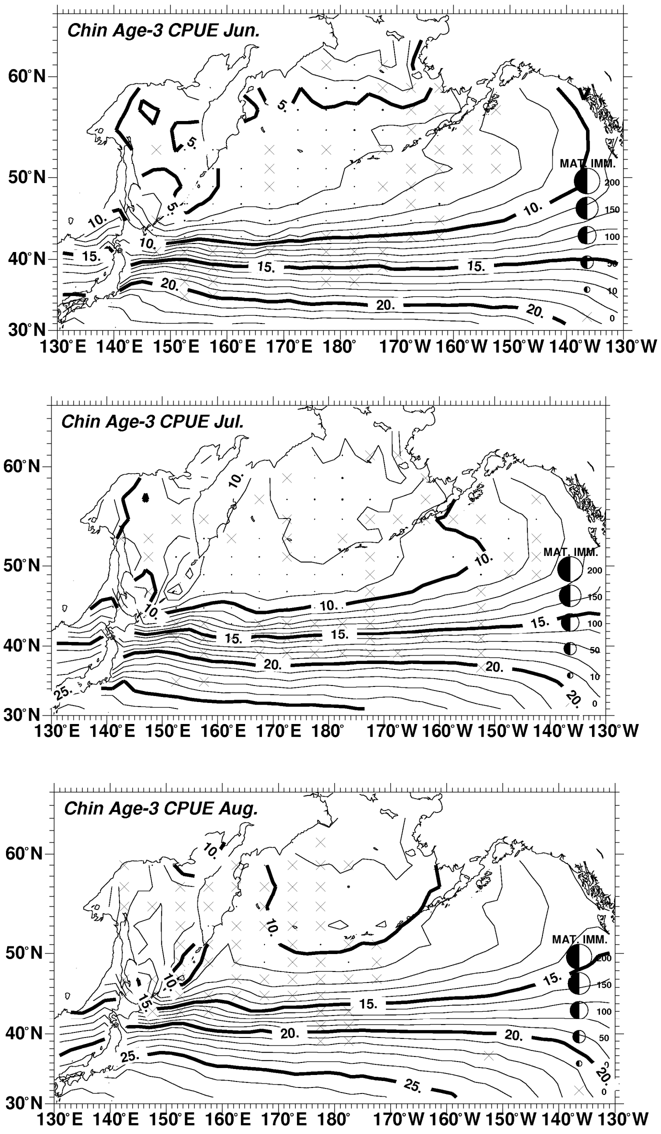

Fig. 12. Monthly ocean distribution of age x.3 Chinook salmon in the North Pacific Ocean. Symbols as in Fig. 1.

DISCUSSION

After overwintering, many populations of Pacific salmon migrate to the Bering Sea to feed. During the summer, age x.1 and age x.2 immature sockeye salmon appeared in the central Bering Sea, although some part of the population remained around the Aleutian archipelago. Recent genetic analysis has revealed that most immature sockeye salmon sampled in the central Bering Sea, were Bristol Bay stocks (Habicht et al. 2005). Thus, both the Bering Sea and the southern portion of the Aleutian archipelago are important feeding grounds for Bristol Bay sockeye stocks. Horizontal distribution patterns in this study showed that older chum salmon intrude into the cool Bering Sea earlier than younger chum in spring, but in summer, the most abundant salmon in the Bering Sea was age 0.1 chum salmon and the second was age 0.2 immature chum salmon. Maturing pink salmon were more abundant in the western part of the North Pacific than in the Bering Sea. Although maturing pink salmon of eastern Kamchatka and western Alaska stocks appear in the Bering Sea in June (Myers et al. 1996), they must return to their natal rivers by August. Maturing coho salmon were relatively rare in the Bering Sea in each month, but abundant in the northern North Pacific Ocean. Although Chinook salmon were rather few, they occurred widely in the Bering Sea and northern North Pacific Ocean from June to August. It seems that the Bering Sea is not an important feeding area for most stocks of coho salmon. Although there are many maturing pink salmon feeding in the Bering Sea, their feeding period is shorter than that of other Pacific salmon which have a longer ocean life. Immature and maturing Chinook salmon appear in all seasons in the central Bering Sea, but

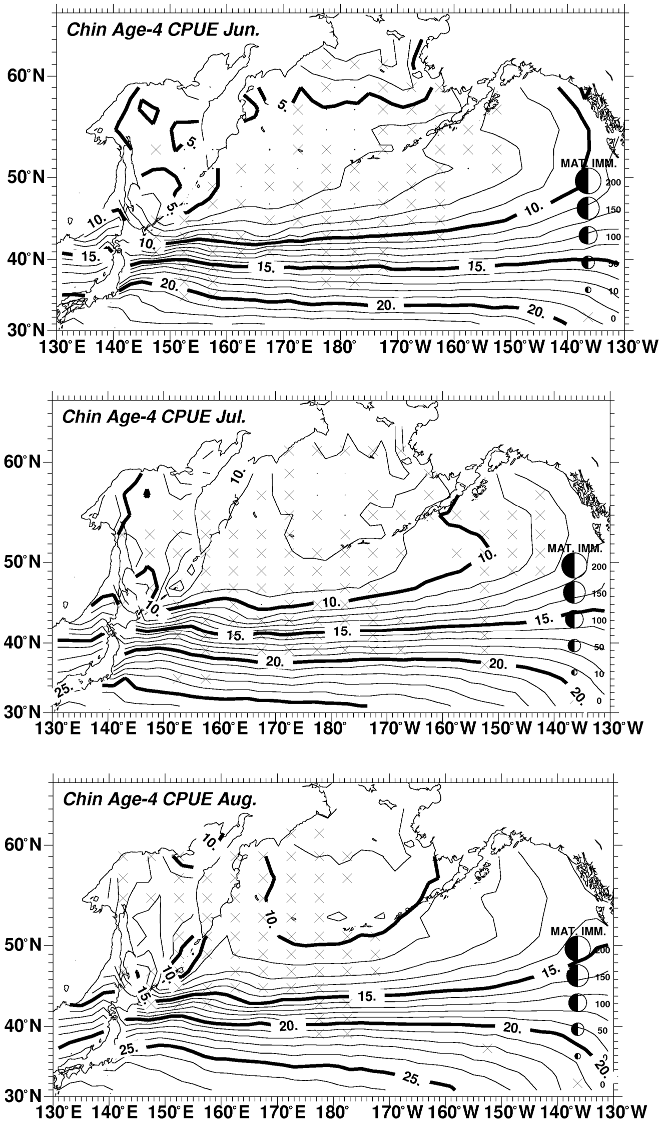

Fig. 13. Monthly ocean distribution of age x.4 Chinook salmon in the North Pacific Ocean. Symbols as in Fig. 1.

the species is not abundant. The Bering Sea is an important feeding area for salmon which have a long ocean life period (chum, sockeye and Chinook salmon). For other salmon, the subarctic region of North Pacific Ocean is a more important area than the Bering Sea, as a feeding migration area.

Azumaya et al. (2007) described the upper and lower thermal limits for 5 Pacific salmon (sockeye, chum, pink, coho, and Chinook salmon) based on data from several BASIS cruises and Japanese research-gillnet operations, however ocean-age differences in thermal limits for each species were not considered. In this study, we showed the different distribution patterns for each ocean-age class. For example, in June, age 0.1 chum salmon occurred at temperatures > 5°C; older chum salmon occurred in waters < 4°C. Apparently, older chum salmon enter the cool Bering Sea earlier than younger chum.

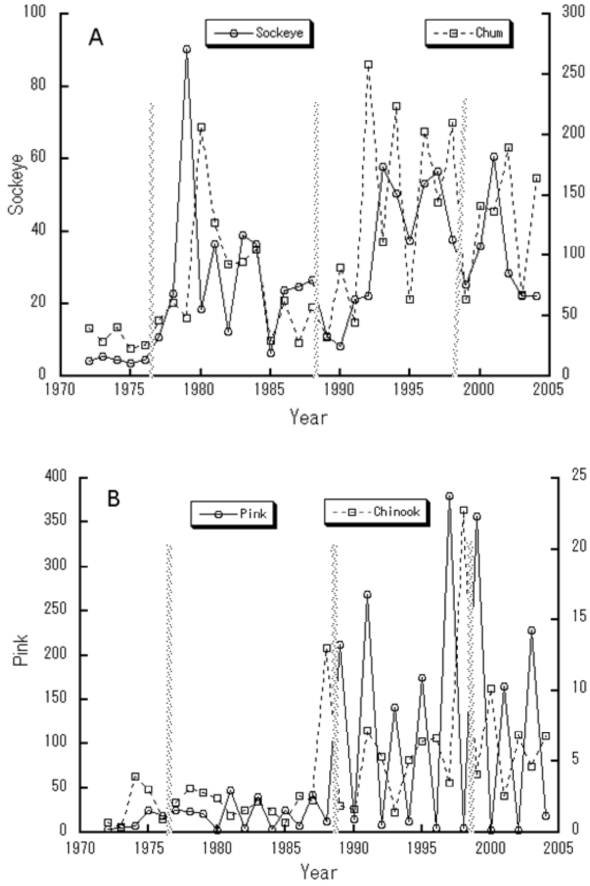

Fig. 14. Mean July CPUE trends in Japanese research-gillnet surveys for four Pacific salmon species in the Bering Sea. Panel A shows sockeye and chum salmon, and Panel B, pink and Chinook salmon, Pale gray vertical lines indicate the hypothesized regime shifts.

In this study, we showed the time series of fluctuations in CPUE in salmon and SST in the Bering Sea from 1972 to recent years. There are two patterns in CPUE fluctuation, one for pink and Chinook salmon, the other for sockeye and chum salmon. The CPUE of pink and Chinook salmon increased and remained at high levels after 1988. Before 1988, the mean CPUE for these two species was rather low. The regime shift in 1988/1989 might have affected the change in these CPUE trends. Based on tagging experiments, most Chinook salmon distributed in the central Bering Sea belong to either the Arctic-Yukon-Kuskokwim (AYK) or Bristol Bay stocks (Major et al. 1978; Myers et al. 1984). However, our CPUE time series trend was very different from the commercial catches of the AYK and the Bristol Bay stocks.

In our data, the 5YRM CPUE trends in sockeye and chum salmon are similar to the 5YRM SST fluctuation. It seems that sockeye salmon densities were higher in warm than in cool periods in the Bering Sea. Some researchers have hypothesized that the ocean condition shifted to a high production regime in 1977 and then shifted back to a low production regime in 1989 (Beamish and Bouillon 1993; Hare and Mantua 2000). However, during the hypothesized

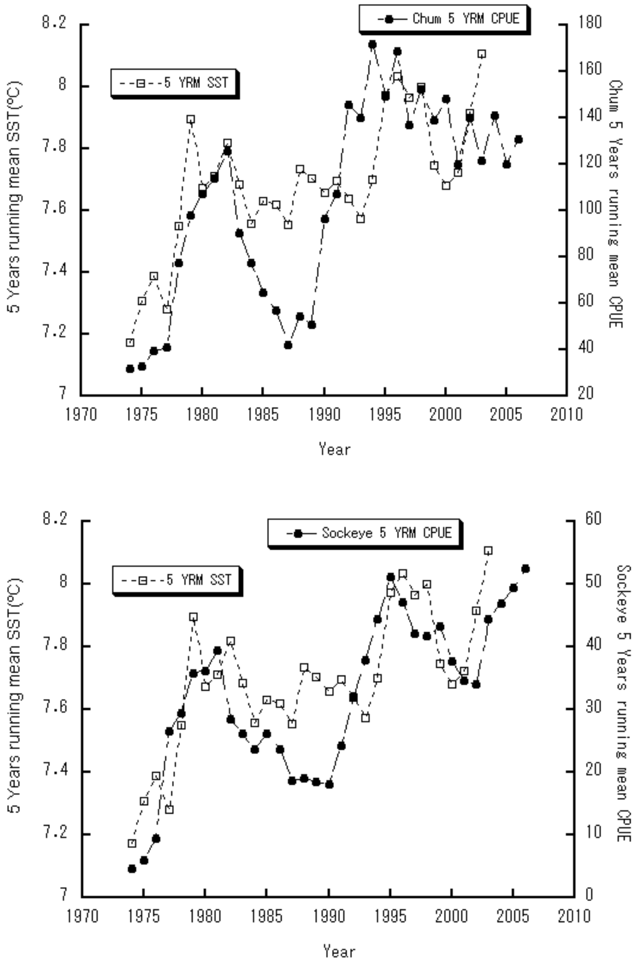

Fig. 15. Trends in 5-year running means (5YRM) for July CPUE (Japanese research vessels) of chum (upper panel), and sockeye (lower panel) salmon in the Bering Sea. Hatched lines indicate the 5-year running mean of July sea-surface temperatures in the Bering Sea.

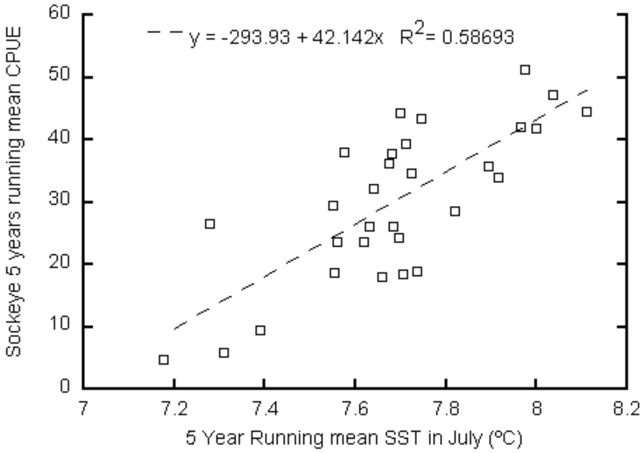

Fig. 16. Relationship between July 5YRM CPUE (Japanese research vessels) in the Bering Sea, and July 5YRM SST in the Bering Sea.

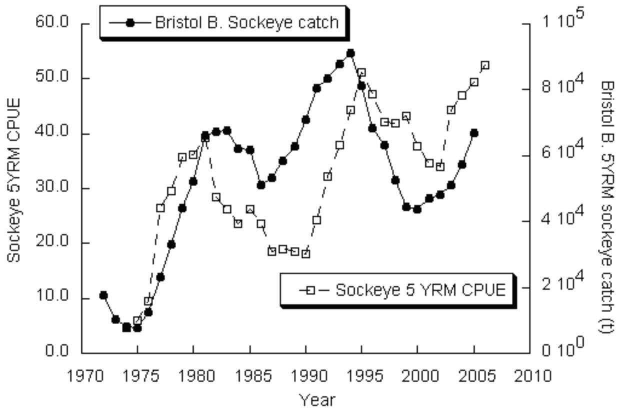

Fig. 17. Five-year running mean trends in the Bristol Bay sockeye salmon commercial catch and 5YRM CPUE (Japanese research vessels) in the Bering Sea.

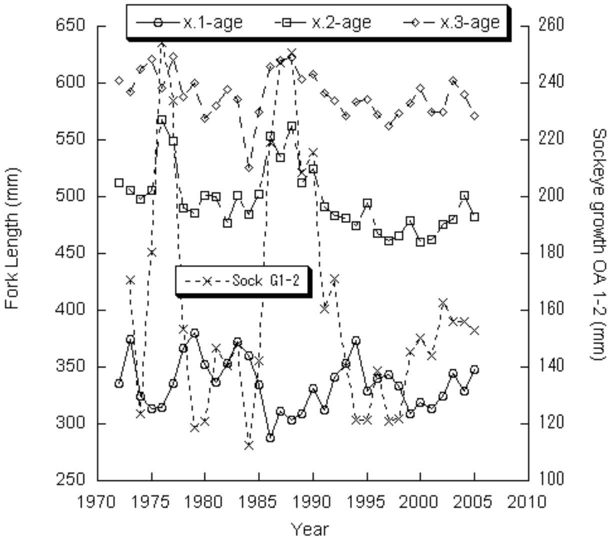

Fig. 18. Trends in mean July fork length of sockeye salmon at each ocean age (x.1, x.2, and x.3), and calculated growth rate between age x.1 and x.2 fish in the Bering Sea.

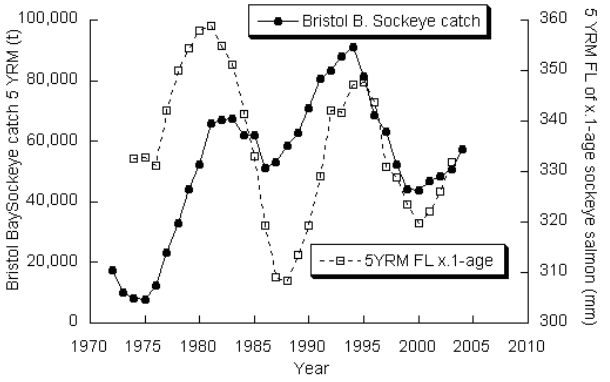

Fig. 19. Trends in the 5YRM sockeye salmon commercial catch in Bristol Bay and the 5YRM July fork length of age x.1 sockeye salmon caught by Japanese research vessels in the Bering Sea.

low production regime, the mean CPUE of four Pacific salmon species (sockeye, chum, pink and Chinook salmon) in the Bering Sea were at high levels. Our data showed a positive linear correlation between 5YRM SST and 5YRM CPUE of sockeye salmon. Additionally, the 5YRM sockeye salmon CPUE oscillation was similar to the 5YRM commercial catch of Bristol Bay sockeye salmon. These results indicate that warm periods lead to a high abundance of Bristol Bay sockeye salmon. We showed the similarity in oscillation patterns between size trends of age x.1 sockeye salmon and abundance of Bristol Bay sockeye salmon stocks. When the 5YRM FL of age x.1 sockeye salmon became large, the Bristol Bay sockeye salmon abundance increased. Farley et al. (2007a) showed that the warmer sea temperatures during the spring and summer increased the productivity in the eastern Bering Sea, enhancing sockeye salmon growth; and Farley et al. (2007b) support the “bigger is better” hypothesis for sockeye salmon (Beamish and Mahnken 2001). Our analysis in the central Bering Sea also supports his hypothesis for sockeye salmon populations.

We observed two periods with small mean FL of age x.1 sockeye salmon from 1972 to 2005. One was from 1974 to 1977, and the other from 1986 to 1989. During these periods, the mean FL of age x.2 and age x.3 sockeye salmon was larger than usual. In both periods calculated growth rates between age x.1 and age x.2 sockeye in summer were very high. On the other hand, during 1978–1984 and 1992–1998 with large mean FL of age x.1 sockeye salmon, the mean FL of age x.2 and age x.3 sockeye salmon were small. These results indicate the occurrence of intra-population, density-dependent effects on growth after age x.1 in sockeye salmon in the Bering Sea. Ruggerone and his colleagues pointed out that the population abundance of Asian pink salmon affected the growth of the Bristol Bay sockeye salmon population, based on scale analysis (Ruggerone et al. 2003, 2005), but they did not mention intra-population competition. In our data, mean pink salmon CPUE in the Bering Sea was low between 1972 and 1989, so interspecies competition between Asian pink salmon and Bristol Bay sockeye salmon stocks should have been at low levels. However, large fluctuations in growth of sockeye salmon at sea occurred during this period. Intra-population competition may be more important than interspecific competition on the growth of Bristol Bay sockeye. Farley et al. (2007a) pointed out that age 0 year walleye pollock were important food items for juvenile sockeye salmon along the eastern Bering Sea shelf. According to a recent assessment, the estimated abundance of age 1 walleye pollock was high around 1979 and 1993, and low around 1988 and 2005 (Ianelli et al. 2008). This fluctuation pattern is similar to the mean FL of age x.1 sockeye salmon in the central Bering Sea (Fig. 20). Considering this, abundance of YOY walleye pollock along the eastern Bering Sea shelf should be one of the key factors affecting the growth and survival of juvenile Bristol Bay sockeye salmon. When age 1 walleye pollock are abundant, we can expect numerous YOY walleye pollock as a food organism for age x.1 sockeye salmon in the eastern Bering Sea. An abundant food supply may accelerate the early growth of age x.0 sockeye salmon in the eastern Bering Sea shelf.

In this study, we showed that SST fluctuations affected some characteristics of Pacific salmon. The SST and other oceanographic components were, in turn, influenced by climate change. Among the climate indices, the PDO was well associated with Alaskan sockeye stocks (Mantua et al. 1997; Hare et al. 1999). The PDO was an index of SST fluctuation; it was also associated with our SST data on the central Bering Sea. The detected regime shifts in the PDO occurred in 1977 and 1989. After the 1977 regime shift, the Bering Sea became warmer and the mean FL of age x.1 sockeye salmon increased until 1985. Mean FL became smaller in 1986 and 1987 (Figs. 18 and 19). After the 1989 regime shift, mean FL of age x.1 sockeye salmon increased until 1995. The

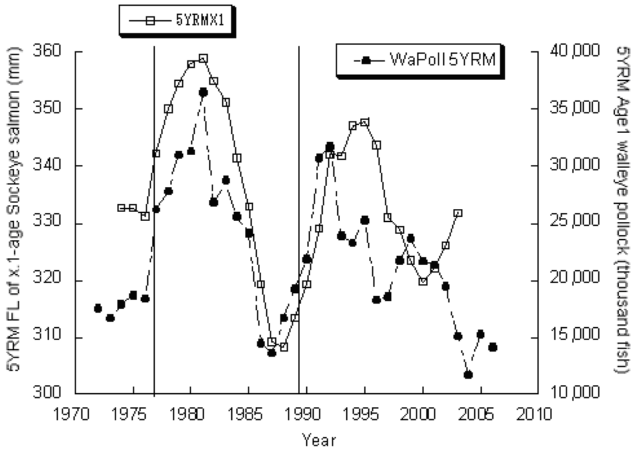

Fig. 20. Trends in the 5YRM July fork length of age x.1 sockeye salmon caught by Japanese research vessels in the Bering Sea, and the 5YRM of estimated abundance of age 1 walleye pollock (from Ianelli et al. 2008) in the Western Bering Sea.

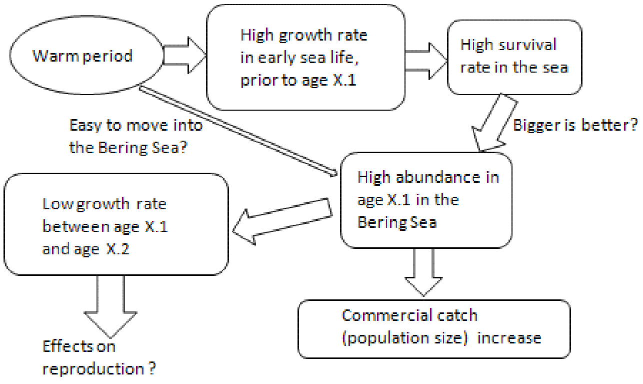

Fig. 21. Suggested connection for some characteristic changes in sockeye salmon stocks that migrate in the Bering Sea during the summer, in warm periods.

1977 regime shift marked a significant increase in many Alaskan salmon stocks (Hare and Francis 1994), but trends after the 1989 regime shift were unclear. Some researchers indicated the occurrence of a 1998 regime shift (Minobe 2002). If it is true, we can now identify three regime shifts, 1977, 1989, and 1998, in our time series of CPUE and SST data in the Bering Sea. Among these three years, both the SST and CPUE showed two up-and-down cycles with the minimum value around each regime shift year. Additionally, we can see a similar trend in the commercial catch of Bristol Bay sockeye salmon. What has happened to sockeye salmon during the warm periods (such as around 1980 and 1996)? We propose a possible process affecting sockeye salmon characteristics in Fig 21. In warm periods, salmon grow faster during early marine life in the eastern Bering Sea, with the larger size resulting in higher survival rates. The result of higher early life survival is a higher abundance of age x.1 sockeye salmon. If, after age x.1, the survival rate of salmon is semi-constant, then a high abundance of age x.1 fish results in an increased commercial catch (population size). Because of intra-population density effects, growth rates between age x.1 and age x.2 sockeye salmon become lower because of the influence of a high density of age x.1 fish. Effects of slower growth rates are unclear, but may affect reproduction through the adult size, fecundity, or egg quality.

In this paper, we have shown the possibility of semi-decadal fluctuations in the Bering Sea SST, and related fluctuations in sockeye salmon abundance, although cause and effects of the fluctuations are still unclear. Climate change and its effects on the salmon populations are one of the serious problems affecting salmon population management (Beamish 2007).

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