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Body Size of Maturing Chum Salmon in Relation to Sea Surface Temperatures in the Eastern Bering Sea

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Abstract: During their last season at sea, some chum salmon from North America and Japan are known to forage in the southeast Bering Sea. Body size of mature chum salmon from North America and Japan was compared with sea surface temperatures in the winter, spring, and summer in the southeast Bering Sea during three time periods: pre-regime shift 1960–76, regime shift 1977–94, and post-regime shift 1995–2006. During the 1977–94 time period, mean correlation coefficients between body size and sea surface temperatures were positive and largest during the winter and spring. During the 1960–76 and 1995–2006 time periods, correlation coefficients were usually smaller and often negative. We conclude that chum salmon from many locations around the Pacific Rim were present in the eastern Bering Sea during the winter and spring of 1977–1994. We suggest that differences in oceanographic parameters and population density of salmon during the three time periods may influence migration pathways of salmon in the North Pacific Ocean and Bering Sea. Research on migration patterns of salmon in relation to these factors is necessary to elucidate these issues.

Keywords: chum salmon, body size, sea surface temperatures, Bering Sea

INTRODUCTION

Chum salmon (*Oncorhynchus keta*) from western Alaska and from as far south as the state of Washington (Fig. 1) can occur in the eastern Bering Sea during their last summer in the ocean (Wilmot et al. 1998). Chum salmon from Japan and Russia also occur in the eastern Bering Sea even during their last summer in the ocean (Wilmot et al. 1998; Urawa et al. 2005, 2009; Sato et al. 2009). Because the last year in the ocean is important in determining final size at maturity in chum salmon (Helle 1979) we suggest that a positive relation between body size at maturity and environmental parameters, such as sea surface temperature (SST), in the Bering Sea would indicate the presence of the chum salmon in that area.

In the Bering Sea, spring temperatures and the timing of the sea ice retreat in the spring are important in determining annual production in the pelagic zone (Napp et al. 2000; Hunt et al. 2002; Jin et al. 2007). During cold years when more ice is present, the spring phytoplankton bloom occurs in March or April, whereas during warm years when the ice retreats earlier, the spring bloom occurs during May or June (Stabeno et al. 2001; Baier and Napp 2003). During warm years, the later timing of the spring phytoplankton bloom coincides with the optimal time for the feeding and growth of zooplankton which, in turn, provides more food for pelagic species such as salmon (*Oncorhynchus* spp.) (Hunt et al. 2002). This is a possible mechanism by which climate change may affect the growth of salmon.

We consider sea surface temperatures (SST) to be a surrogate for prey availability for chum salmon in the eastern Bering Sea. Thus, we examine the relation between SST in the winter/spring/summer and body size of chum salmon from North America and Japan during three time periods: pre-ocean regime shift, 1960–1976; ocean regime shift, 1977–1994; and post- ocean regime shift, 1995–2006 (Helle et al. 2007). Our hypothesis is that body size of mature chum salmon in the eastern Bering Sea that relates positively to SST during their last growth season at sea suggests their presence in the eastern Bering Sea.

MATERIALS AND METHODS

Size data used for this study of chum salmon from North America are from Helle et al. (2007). Data on body size of chum salmon from Japan are from Fukuwaka et al. (2007). For the years 1960–2006 body sizes of maturing chum salmon of North American and Japanese (Hokkaido) origin were compared to winter, spring, and summer SST in the southeastern Bering Sea during climate-ocean regime periods.

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Mean Body Weight Estimates

Mean body size of Pacific salmon during the year of migration back to natal rivers were estimated from commercial fisheries harvest statistics from Kotzebue in northern Alaska to the state of Washington from 1960 to 2006 (Helle et al. 2007). Mean body size was calculated as the total biomass (kg) of chum salmon captured during year t divided by the numbers of salmon captured (N) during year t (Helle et al. 2007). Regions included Kotzebue, Norton Sound, Kuskokwim, Yukon (both summer and fall runs), Bristol Bay, central Alaska, southeast Alaska, northern British Columbia, and the state of Washington (Fig. 1). Mean size of central Alaska chum salmon was calculated as the average of the mean body sizes of chum salmon from the Alaska Peninsula, Chignik, Kodiak, Cook Inlet, and Prince William Sound areas. Weights were not available for chum salmon of Japanese origin. Fork length measurements of chum salmon from Japan were available from fish that returned to the Ishikari River on the Japan Sea coast of Hokkaido Island (Fukuwaka et al. 2007). We did not have size-at-age information for the stocks discussed in this paper. However, we are aware that differences in size-at-age or maturation of chum salmon could influence the interpretation of our results (see Helle and Hoffman 1995). In addition, we have not attempted to evaluate the complex effects of gear selectivity on body size of commercial salmon catches. We assume the correlations between body size and SST in each area are valid.

Sea Surface Temperature (SST)

Winter, spring, and summer SST in the eastern Bering Sea were used to reflect ocean conditions experienced by salmon in the eastern Bering Sea. These were compared to body sizes of adult salmon returning to the eastern and western North Pacific Ocean. The three SST periods used were: January 15–April 15 (winter), May (spring), and June, July, and August (summer). The winter, spring, and summer SST periods also reflect climatic processes that occurred during the past winter: ice cover ($r = 0.50$; $P < 0.05$), winter surface air temperatures on St. Paul Island in the southeast Bering Sea ($r = 0.59$; $P < 0.01$), spring wind mixing, and the summer bottom temperature ($r = 0.82$; $P < 0.001$) for the period 1982–2003 (www.beringclimate.noaa.gov). Sea surface temperatures recorded at the Mooring 2 buoy (M2, 57°N, 164°W) were available from the National Oceanic and Atmospheric Administration's Bering climate website (http://www.beringclimate.noaa.gov) and Pacific Marine Environmental Laboratory staff. Winter, spring, and summer SST had been calculated as an average monthly sea surface temperature from the NCEP/NCAR Reanalysis at M2 in the southeastern Bering Sea (54.3–60.0°N, 161.2–172.5°W). The SST data are from the NCEP/NCAR Reanalysis project (Kalnay et al. 1996). Before 1982, the NCEP data are the

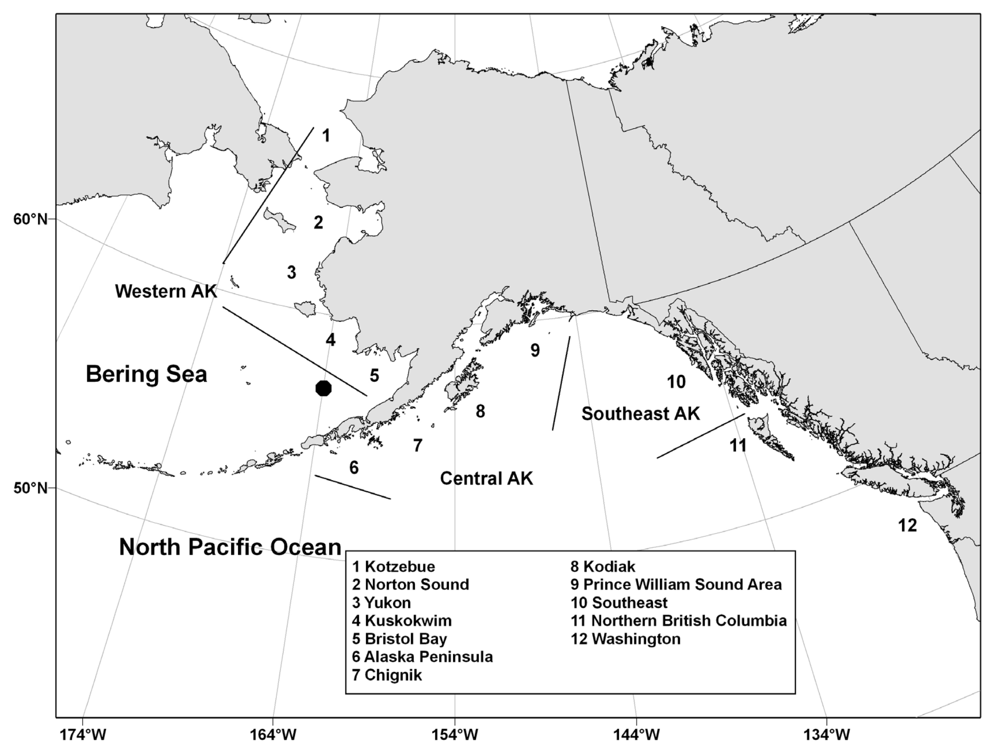

Fig. 1. Locations of salmon populations examined for changes in body size over time in Alaska (AK) (U.S.A.), British Columbia (Canada), and Washington (U.S.A.). The black dot marks the location of the biophysical mooring site M2 in the eastern Bering Sea. Mooring operated by NOAA, Pacific Marine Environmental Laboratory, Seattle, Washington.

optimally interpolated *in situ* SST based on the Reynolds and Smith reanalysis (1994). From 1982–2006, the NCEP analysis used both *in situ* and satellite data.

Relation between Body Size and SST

The Pearson product moment correlation coefficient was used to describe the relationships between mean body size of salmon populations and SST in the Bering Sea. The coefficient measures the tendency of the variables to increase or decrease together. The coefficient is calculated by dividing the covariance between the two variables by the product of their standard deviations. We decided not to test the significance of individual correlation coefficients because we were looking for regional patterns over time.

Comparisons were made between salmon body size and SST during three time periods. The periods were: pre-ocean regime change, 1960–76; ocean regime change, 1977–94; and post-ocean regime change, 1995–2006. Designations for these time periods were the same used by Helle et al. (2007). The post-ocean regime change was estimated to have begun in 1995 because chum salmon size in North America increased in 1994–1995 after declining from the late 1970s through the early 1990s (Helle and Hoffman 1995; Helle et al. 2007). Comparisons were made between salmon size and SST in the eastern Bering Sea because some populations from North America are known to migrate from the North Pacific Ocean to the Bering Sea (Myers et al. 1996; Wilmot et al. 1998).

RESULTS

Sea Surface Temperatures in the Eastern Bering Sea

Multi-year and annual variation occurred in the average SST in the eastern Bering Sea during January-April from 1960–2006 (Fig. 2). Multi-year variation indicates that temperatures were warm in 1960–70, cool in 1971–76, warm in 1977–80, cool in 1982–2002, warm in 2003–05, and cool in 2006. Temporal trends show SST dropped steeply between 1969 and 1976, rose between 1976 and 1977, and declined from 1981 through 1992. The coolest years were 1964, 1971, 1973–76, 1992, and 1999. The warmest years were 1969, 1977–1981, 2001, 2003, and 2005.

Sea surface temperatures over time in spring and summer showed much less variation than winter temperatures (Fig. 2). Comparisons of SST during the three seasons within each time period again show the most variation during winter (Fig. 3).

Relation between Body Size and Sea Temperature

Time series graphs of body size and SST for winter, spring, and summer and three time periods within each season are presented in Figs. 4–12. Generally, the correlation coefficients were small or negative during 1960–76 in all three seasons (Table 1). The largest correlation coefficient between body size and SST during the 1960–76 time period was -0.31 for Japanese male chum in winter (Table 1). For

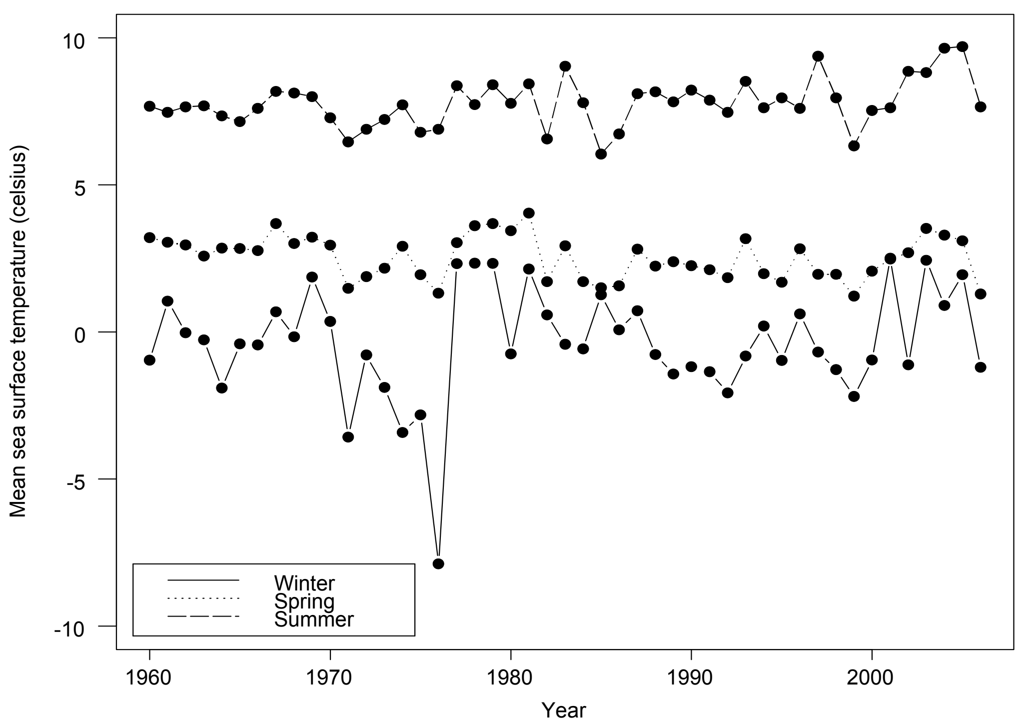

Fig. 2. Mean sea surface temperatures at the M2 mooring buoy during winter (January–April), spring (May), and summer (June–August) in the eastern Bering Sea from 1960 to 2006.

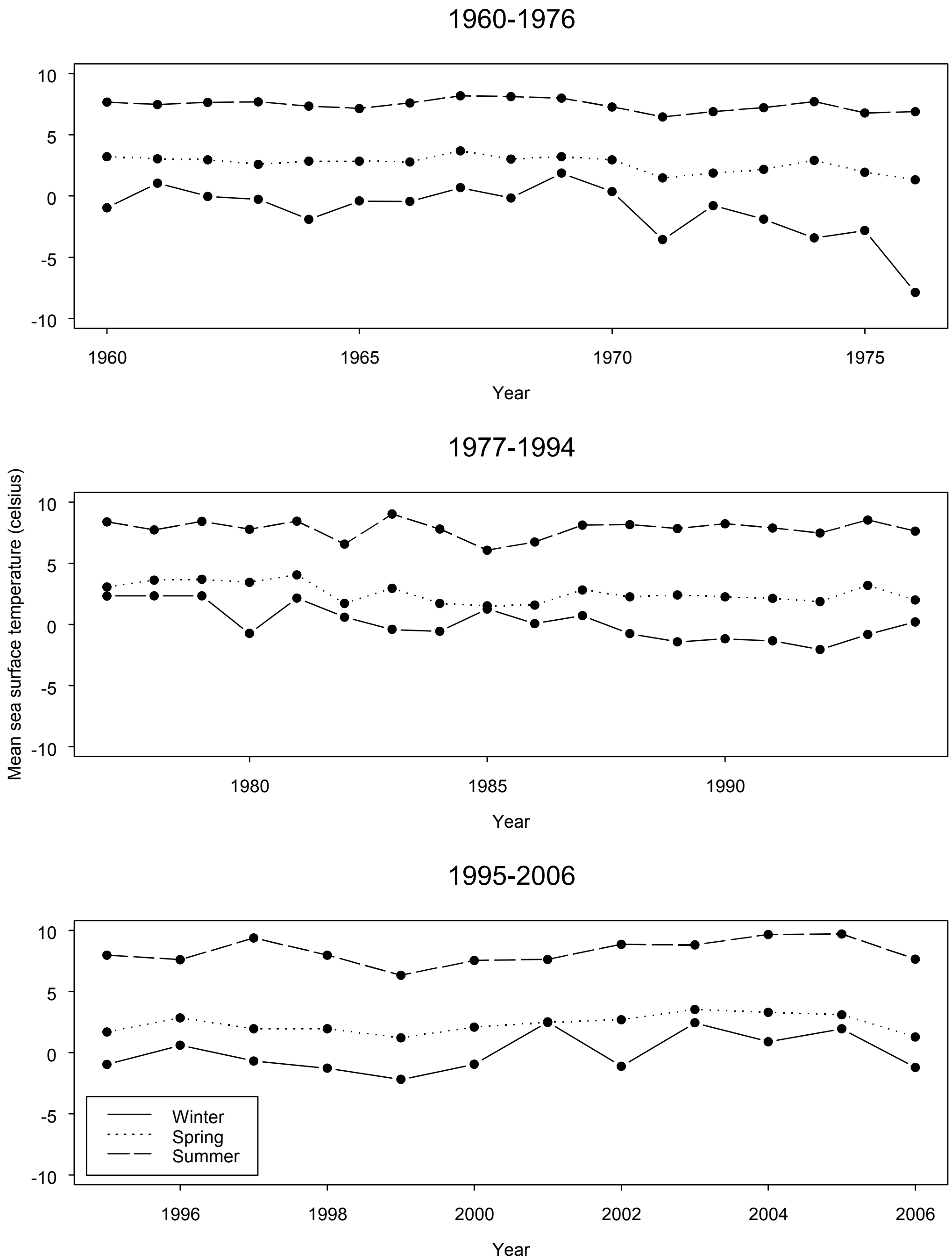

Fig. 3. Mean sea surface temperatures at the M2 mooring buoy in winter (January–April), spring (May), and summer (June–August) in the eastern Bering Sea during three time periods: 1960–1976, 1977–1994, and 1995–2006.

the 1977–94 time period, correlation coefficients were mostly positive. During the 1995–2006 time period, mean correlation coeffients were smaller than those in 1976–94. Nearly all of the correlation coefficients from central Alaska south to the state of Washington were negative from all three SST databases (Table 1). Seasonally, the mean positive correlation coefficients decreased from winter to summer for the 1977–94 and 1995–2006 time periods.

Winter

Winter SST was more positively correlated with body size than spring or summer SST for the 1977–94 and 1995–2006 time periods. Little relation is evident between body size and winter SST in 1960–76 (Fig.4). However, body size and winter SST comparisons tended to track quite closely during 1977–94 (Fig. 5). Correlation coefficients between body size and winter SST were generally larger and positive

Table 1. Pearson correlation coefficients relating mean body size of chum salmon to mean sea surface temperature (SST) in the eastern Bering Sea during winter (January–April), spring (May), and summer (June–August). Correlations were not computed when less than 10 years of paired data were available.

Area	Winter SST			Spring SST			Summer SST		
	1960–1976	1977–1994	1995–2006	1960–1976	1977–1994	1995–2006	1960–1976	1977–1994	1995–2006
Japan females[1]	0.10	0.68	0.18	0.25	0.72	0.19	0.26	0.22	0.05
Japan males[1]	-0.31	0.59	0.16	-0.21	0.54	0.32	-0.21	0.15	0.11
Kotzebue	–	0.48	0.38	–	0.38	0.51	–	0.18	0.17
Norton Sound	–	0.35	-0.02	–	0.39	0.05	–	0.19	-0.07
Yukon River summer	–	0.17	0.40	–	0.31	0.41	–	0.23	-0.06
Yukon River fall	–	0.61	–	–	0.59	–	–	0.47	–
Kuskokwim	–	0.63	-0.27	–	0.34	-0.15	–	0.09	-0.30
Bristol Bay	-0.06	0.63	0.51	0.07	0.24	0.34	0.04	0.07	0.11
Central Alaska	-0.23	0.48	-0.35	0.10	0.08	-0.46	0.28	0.003	-0.45
Southeast Alaska	-0.20	0.45	-0.52	0.12	0.28	-0.48	0.24	-0.02	-0.41
N. British Columbia	–	0.42	-0.29	–	0.47	-0.38	–	0.22	-0.58
Washington	–	0.45	-0.54	–	0.23	-0.44	–	-0.02	-0.15
Mean positive correlations	0.10	0.50	0.33	0.13	0.38	0.30	0.21	0.18	0.11

[1]Mean fork lengths of four-year-old chum salmon from the Ishikari River were used in calculating the correlations with mean sea surface temperature.

during the 1977–94 time period. The largest correlation coefficients during 1977–94 in winter were from Japanese and western Alaska chum populations. During 1995–2006, the comparisons between body size and winter SST were often negative, especially from central Alaska populations south to the state of Washington (Fig. 6).

Spring

Spring SST and mean body size correlation coefficients were larger for the 1977–94 (R = 0.38) and 1995–2006 time periods (R = 0.30), and smaller for the 1960–76 time period (R = 0.13). Similar to the comparison with body size and winter SST in 1960–76, the comparison of body size with spring SST shows little relation (Fig. 7). There appears to be a strong relation between body size and spring SST in both female and male Japanese chum salmon; however, the rest of the stocks compared with spring SST during this time were quite variable (Fig. 8). During the 1977–94 time period, correlation coefficients between body size and spring SST were largest from Japanese, Yukon River Fall, and Northern British Columbia stocks (Table 1). During the 1977–94 time period, correlation coefficients between body size and spring SST were generally lower than they were in winter with two exceptions – Japanese female chum and northern British Columbia chum. During 1995–2006 time period, the comparison of body size and spring SST, like the winter SST in 1995–2006, there was a tendency toward a negative relation in the stocks from central Alaska south to the state of Washington (Fig. 9).

Summer

The mean positive correlations between body size and SST were smaller in summer than in winter and spring. The mean positive correlations in the summer were largest in 1960–76 (R = 0.21) and 1977–94 (R = 0.18), and smaller in 1995–2006 (R = 0.11). Comparison of body size and summer SST of five populations during 1960–76 shows little relation (Fig. 10). Comparison of body size and summer SST during both 1977–94 and 1995–2006 also show little relation (Figs. 11 and 12). During the 1977–94 time period, the mean positive correlation coefficients between body size and summer SST were all smaller than those during winter or spring (Table 1). During the 1995–2006, the correlation coefficients for body size and summer SST were all negative as was seen with winter and spring SST.

DISCUSSION

Body size of adult chum salmon, pink salmon (*O. gorbuscha*), and sockeye salmon (*O. nerka*) from Alaska south to the state of Washington was negatively related to interspecific and intraspecific population abundance from 1977 to 1994 (Helle et al. 2007). Salmon body size declined significantly as population numbers increased from 1977 through the early 1990s (Ishida et al. 1993; Helle and Hoffman 1995; Bigler et al. 1996). This relationship between body size (weight) and population abundance was not strong during time periods before 1977 (1960–1976) and after 1994 (1995–2005), even though body size was generally larger after 1994 (Helle et al. 2007). Because body size increased abruptly after 1994, Helle and Hoffman (1998) suggested that there may have been an ocean regime shift. Of these three time periods, the period between 1995 and 2005 was the most favorable for salmon because ocean resources supported salmon of both large size and large population abundance (Helle et al. 2007). Shuntov and Temnykh (2009) in this volume

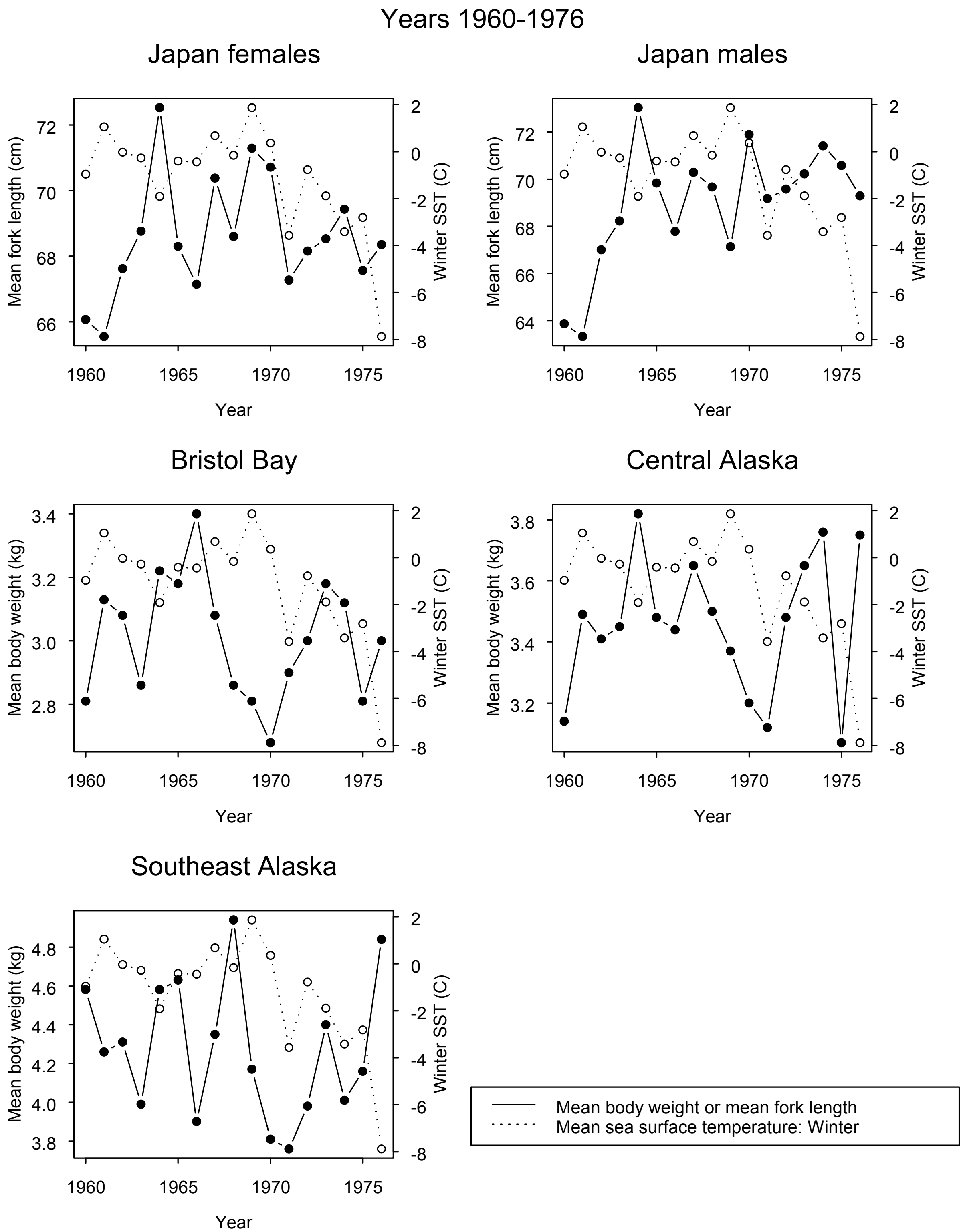

Fig. 4. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in winter (January–April) for chum salmon populations during the 1960–1976 time period.

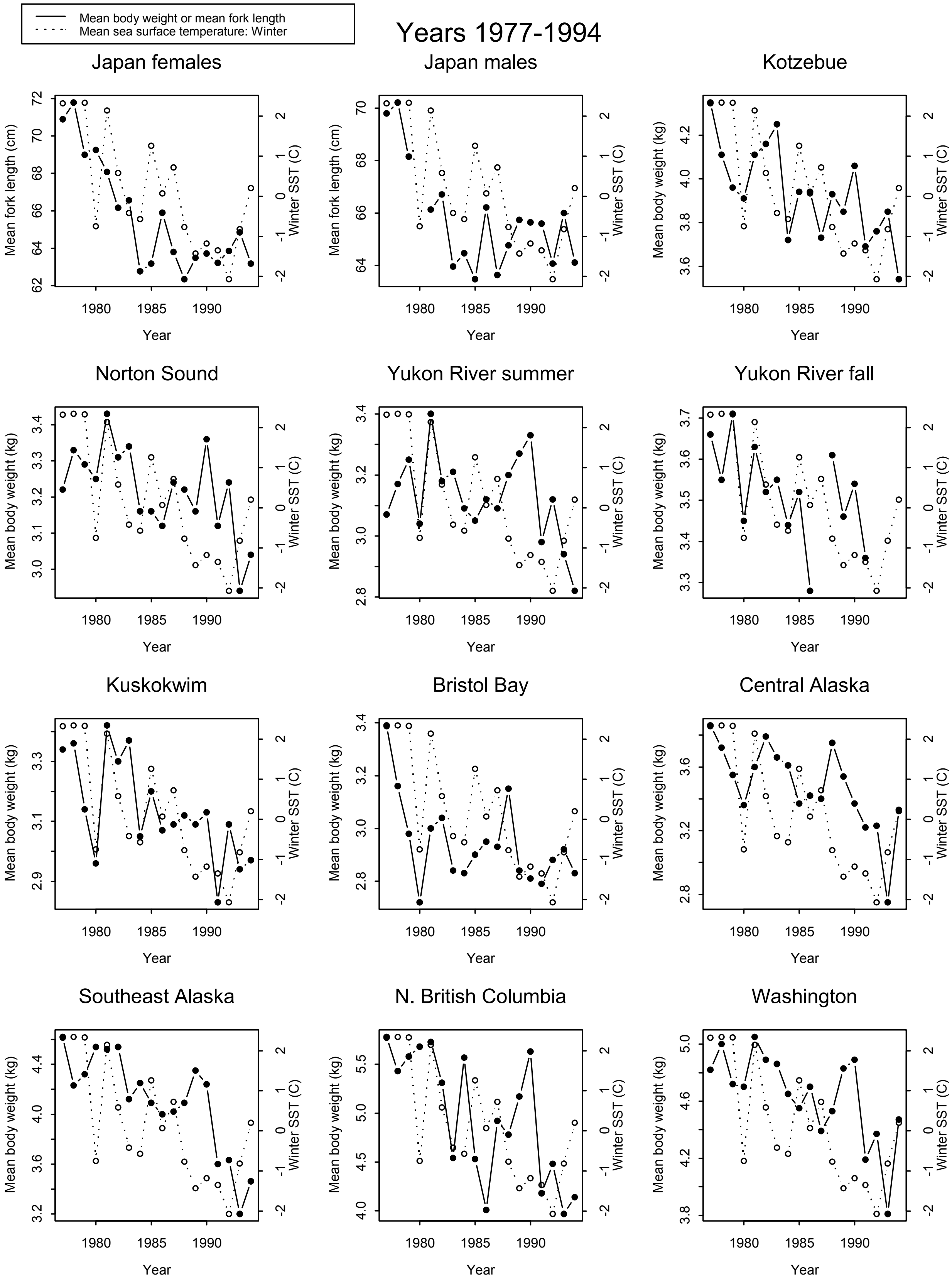

Fig. 5. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in winter (January–April) for chum salmon populations during the 1977–1994 time period.

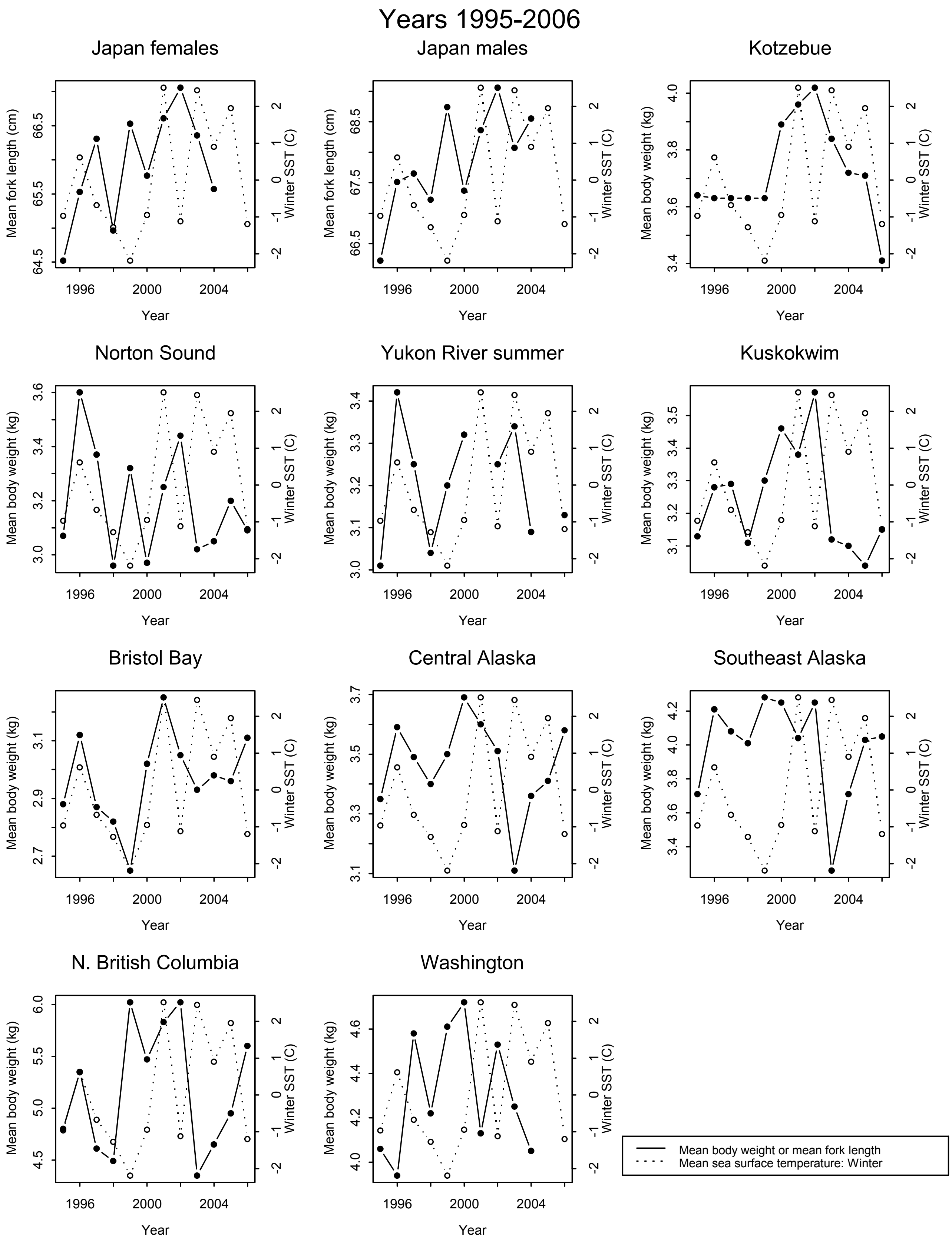

Fig. 6. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in winter (January–April) for chum salmon populations during the 1995–2006 time period.

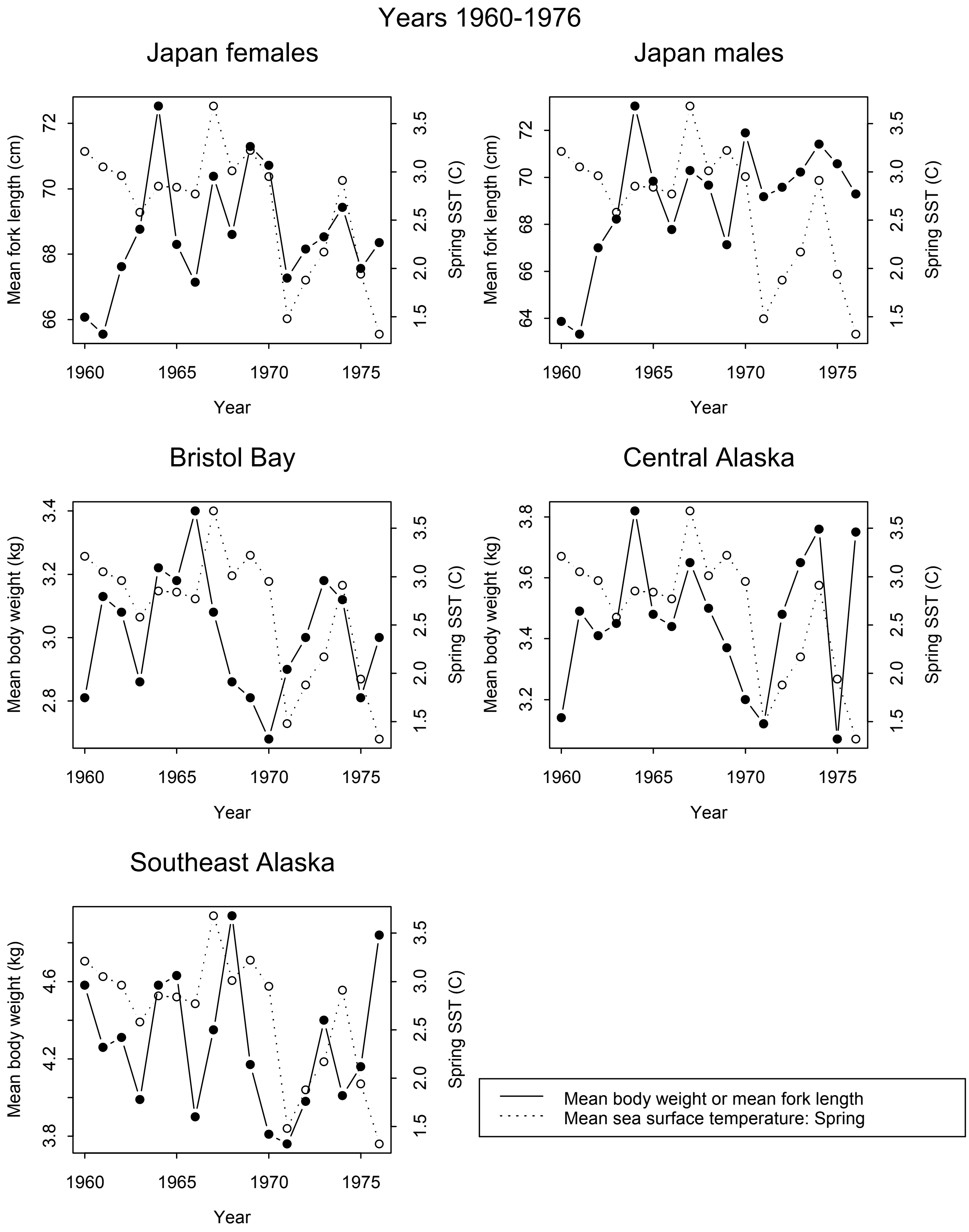

Fig. 7. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in spring (May) for chum salmon populations during the 1960–1976 time period.

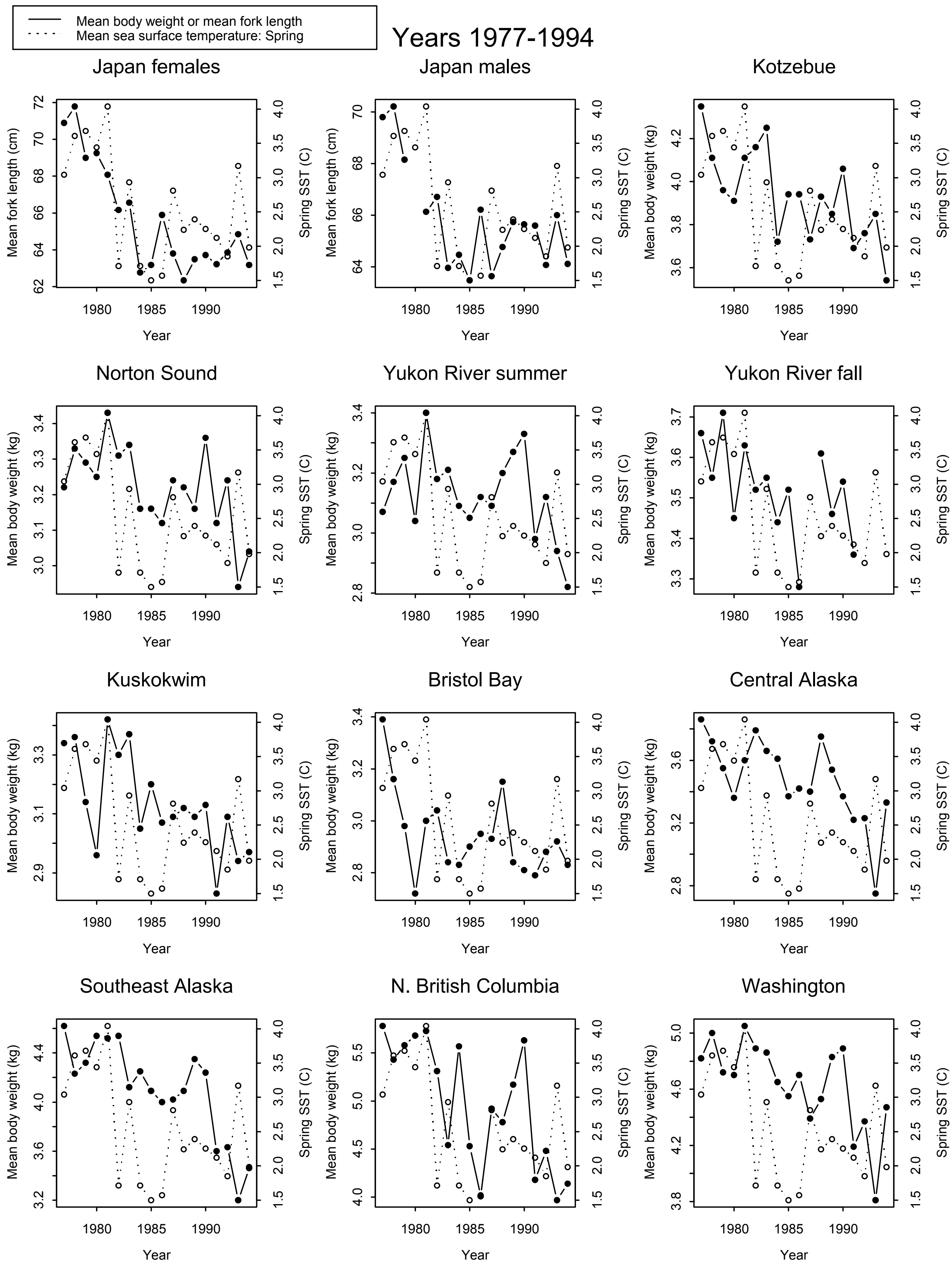

Fig. 8. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in spring (May) for chum salmon populations during the 1977–1994 time period.

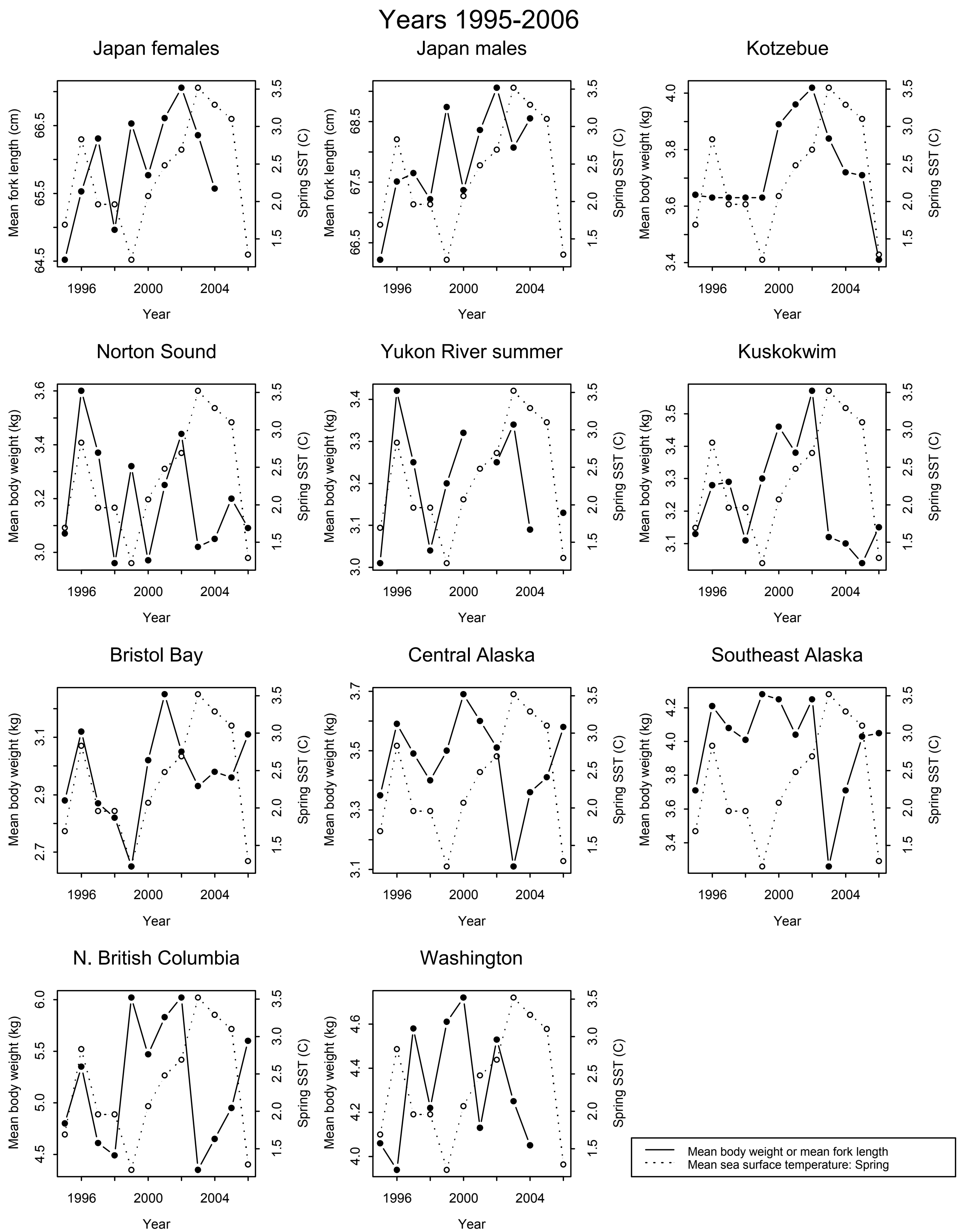

Fig. 9. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in spring (May) for chum salmon populations during the 1995–2006 time period.

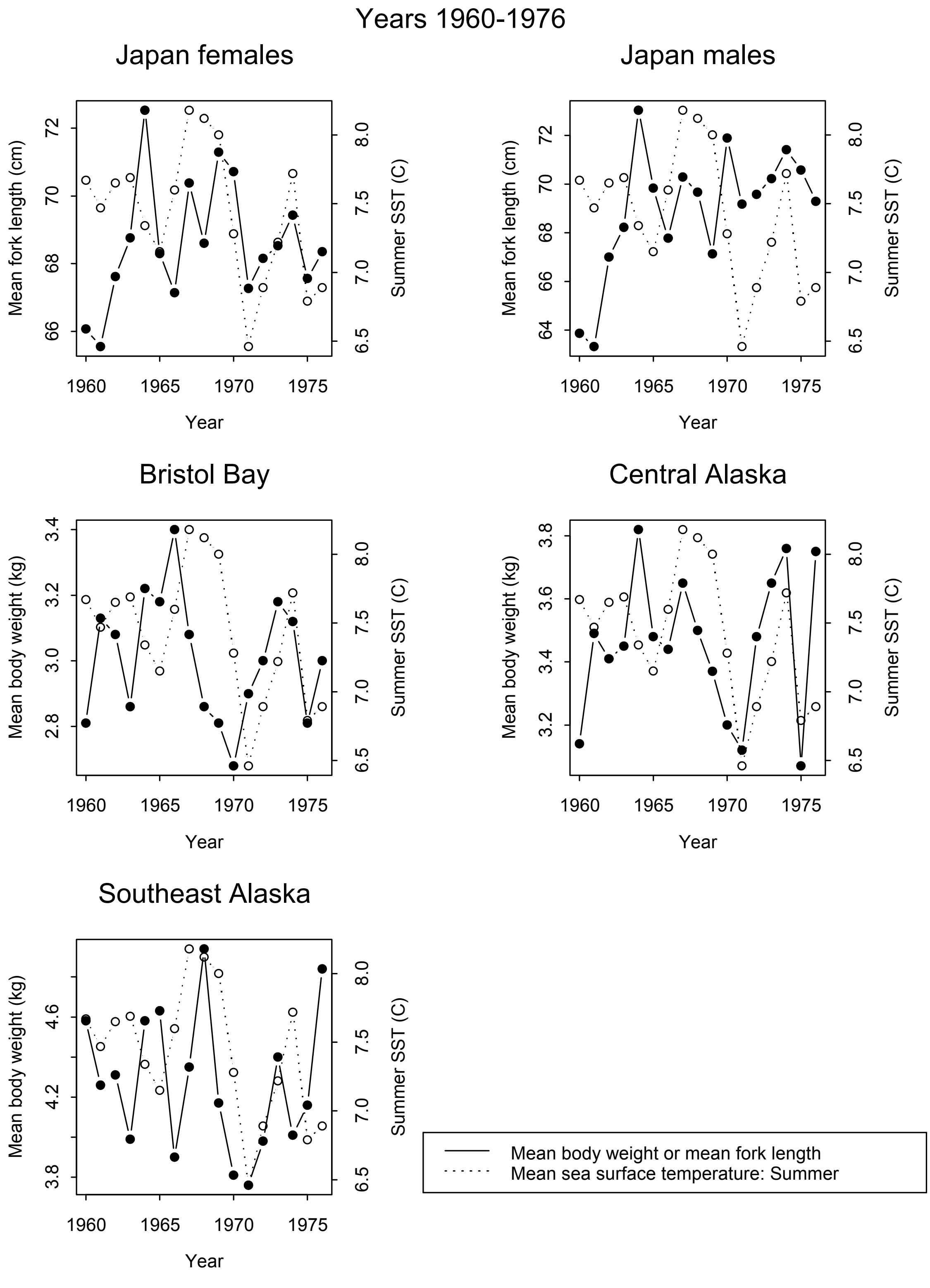

Fig. 10. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in summer (June–August) for chum salmon populations during the 1960 –1976 time period.

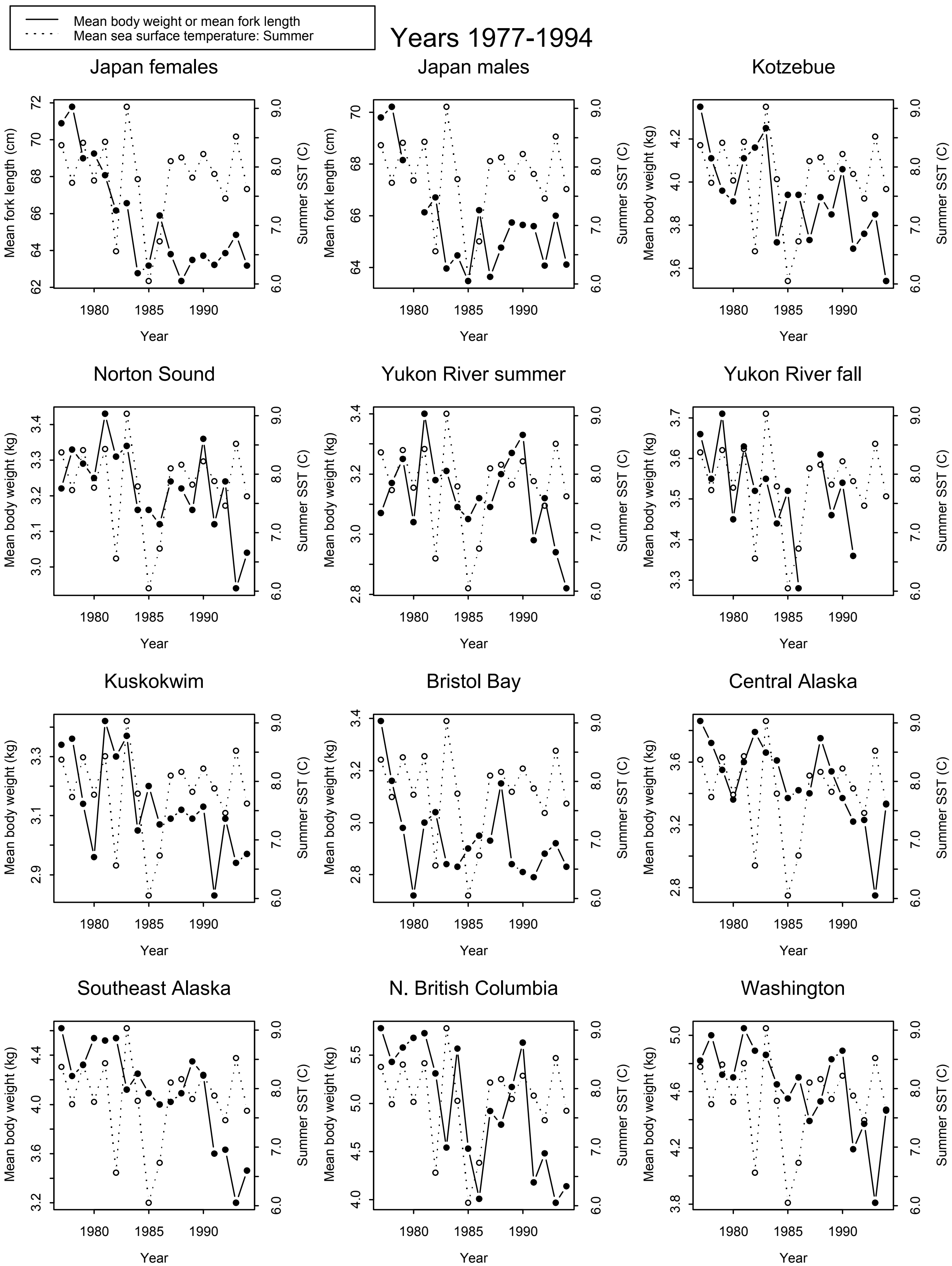

Fig. 11. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in summer (June–August) for chum salmon populations during the 1977–1994 time period.

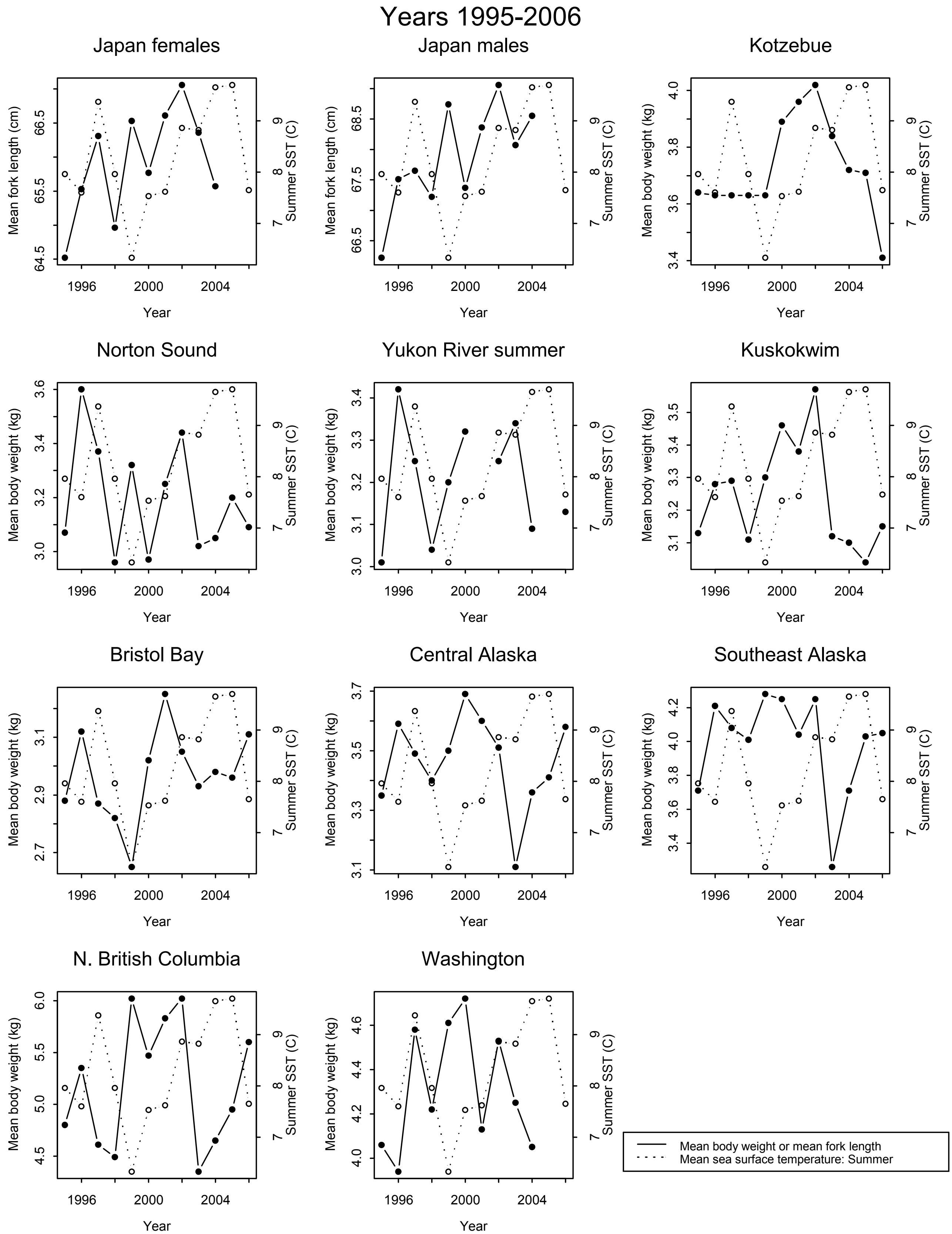

Fig. 12. Time-series of mean body weight or fork length (solid circles and lines) and sea surface temperatures (open circles and dotted lines) in summer (June–August) for chum salmon populations during the 1995–2006 time period.

provide a comprehensive discussion of biological reponses to climate and ocean regime changes in the Bering Sea.

The last year in the ocean is important in determining final size at maturity in chum salmon (Helle 1979). Chum salmon from western Alaska and from as far south as the state of Washington can occur in the eastern Bering Sea during their last summer in the ocean (Wilmot et al. 1998). Chum salmon from Japan and Russia also occur in the eastern Bering Sea during their last year at sea (Wilmot et al. 1998; Urawa et al. 2005, 2009).

Correlation analysis was used to estimate the relation between body size and SST. Correlation coefficients were positive between the body size of adult salmon and winter SST in the eastern Bering Sea for the 1977–94 time period, and mixed positive and negative in 1960–76 and 1995–2006. Also, correlation coefficients were mostly larger during the 1977–94 time period compared to values during 1960–76 and 1995–2006.

Winter SST at the M2 buoy present a measure of the severity of the winter over the shelf of the southeast Bering Sea (Bond and Adams 2002). The oceanographic and climate changes associated with the anomalously cold winters and springs from 1971–1976 (McLain and Favorite 1976) are clearly represented in the winter SST data from the M2 mooring. The dramatic warming between 1976 and 1977 is also documented in the M2 mooring data and is known as the Ocean Regime Shift (ORS) of 1976–77 (Pearcy 1992; Miller et al. 1994; Hare and Francis 1995). Cooling of the sea surfaces in the eastern Bering Sea from the early 1980s through 1992 coincided with a reduction in the body size of salmon as indicated by the generally larger correlations between body size of salmon and SST during the 1977–94 period.

Several mechanisms could explain why body size was positively related to SST during the period following the ORS during the 1977–94 period when body size was declining. One factor that may influence the coincidental reductions in body size of salmon and the cooling of SST is increased competition for food resources among chum, pink, and sockeye salmon (Martinson et al. 2008; Helle et al. 2007; Ruggerone et al. 2003).

Winter/spring SST increases are thought to increase the metabolic rates of zooplankton and fish (Hunt et al. 2002). Possibly, the decline in body size was linked to reduced annual pelagic production that was, in turn, related to the change in the timing of the ice retreat and the spring bloom.

Perhaps differences in the occurrence of larger correlation coefficients between SST and body size among the three time periods are related to the migration routes of maturing salmon. Previous studies have indicated that maturing and immature chum salmon populations from Washington, British Columbia, southeast Alaska, central Alaska, western Alaska, and Asia are at times present in the eastern Bering Sea (Urawa et al. 2005; Wilmot et al. 1998). There could have been more of these Pacific Rim populations in the eastern Bering Sea following the ORS (1977–94) than were present in the periods before and after the ORS. Correlation coefficients were larger between body size and winter SST of chum salmon from the more southerly areas of the eastern Bering Sea and Japan in 1977–94 compared to chum salmon from the more northerly areas of the eastern Bering Sea and eastern North Pacific Ocean. For example, we found that correlation coefficients between body size and winter SST from the southeastern Bering Sea were higher than those for chum salmon from the eastern North Pacific. These differences may indicate a more localized stock-specific response to changes in SST.

During the 1977–94 time period, correlation coefficients were on average lower and positive between body size and spring SST than they were between mean body size and winter SST (Table 1). Perhaps most of the populations we compared were present in the eastern Bering Sea before May. Sea surface temperature and body size correlation coefficients were on average lower during the summer than they were in the spring. Most of the western Alaska chum salmon populations are entering the rivers during June and July so correlation coefficients between body size and summer SST would be expected to be lower. The Yukon River Fall chum salmon population had the largest correlation coefficient during this time and would be expected to be in the eastern Bering Sea later than most of the other populations.

For the 1995–2006 time period, the largest correlations were between winter SST and the body size of chum salmon from Bristol Bay, southeast Alaska and the state of Washington. The Bristol Bay area is within the front of the ice edge in the spring, therefore this stock, if present at that time, would be expected to respond to temperature changes in the area. The correlation coefficient for Bristol Bay was positive while the correlation coefficients for populations from central Alaska south to the state of Washington were negative. The central Alaska, southeast Alaska, and North British Columbia populations showed much steeper declines in body size in 2003 than did the Bristol Bay population. Perhaps these populations were not present in the southeastern Bering Sea at that time. During the 1960–1976 time period, correlations between winter SST and body size were generally low and mostly negative. Stock distribution in the eastern Bering Sea needs to be monitored to understand the results of our analyses.

For most of the southern populations, correlation coefficients between body size and winter and spring SST were mostly negative during the 1995–2006 time period and positive for these populations in 1977–94. During the 1977–94 time period, body size of both North American and Japanese populations was generally large (although decreasing after 1980), population abundances were increasing, and sea surfaces were cooling (Helle et al. 2007; Fukuwaka et al. 2007). During the 1995–2006 time period, chum salmon body size increased abruptly in the mid-1990s but did not reach sizes comparable to those during the early 1970s, population abundances were high but decreasing, and sea surfaces were warming. Warmer SST that resulted in higher productivity during the 1995–2006 time period may have reduced the density-dependent effects of large population abundances on growth rates of chum salmon. On the other hand, these fish may not have been present in the eastern Bering Sea.

The purpose of our study was to learn if SST in the eastern Bering Sea were related to body size of maturing chum salmon from North America and Japan. We assumed that larger correlation coefficients between body size and SST would indicate the presence of those populations in the eastern Bering Sea. Larger correlations between body size and SST were more common during 1977–94 than they were during either 1960–76 or 1995–2006. Helle et al. (2007) found that the relation between body size of chum, pink, and sockeye salmon and population abundance was also stronger during the 1977–94 time period. They found that population abundance was also larger during 1977–94. Perhaps population density was responsible for southern chum salmon populations moving up into the Bering Sea during 1977–94. Understanding stock distribution in relation to SST, prey availability and population abundance may be necessary to account for differences we have observed among these parameters and the three time periods.

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