Long-term Changes in the Climate and Ocean Environment in the Okhotsk Sea and Western North Pacific and Abundance and Body Weight of East Sakhalin Pink Salmon (*Oncorhynchus gorbuscha*)

Kazuya Nagasawa
National Research Institute of Far Seas Fisheries, Fisheries Agency of Japan,
5-7-1 Orido, Shimizu, Shizuoka 424-8633, Japan

* * *

Nagasawa, K. 2000. Long-term changes in the climate and ocean environment in the Okhotsk Sea and western North Pacific and abundance and body weight of East Sakhalin pink salmon (*Oncorhynchus gorbuscha*). N. Pac. Anadr. Fish Comm. Bull. No. 2: 203–211.

Keywords: Pink salmon, climate change, Aleutian Low, sea ice, population biology, zooplankton biomass, carrying capacity

Abstract: Trends in catch of East Sakhalin pink salmon (*Oncorhynchus gorbuscha*) were closely related to the climate and ocean environment in the Okhotsk Sea and western North Pacific. During the period when the intensity of the Aleutian Low strengthened from 1977 to 1988, the area of sea ice expanded in the Okhotsk Sea, but both sea surface temperature (SST) and zooplankton biomass decreased in the western North Pacific, and pink salmon catch declined. Conversely, after the Aleutian Low weakened in 1989, the area of sea ice sharply decreased in the Okhotsk Sea, and pink salmon catch dramatically increased. It is thus suggested that during the period of the intensified Aleutian Low, juveniles have a higher mortality due to decreased SST in the Okhotsk Sea, and overwintering immature fish have a higher mortality due to decreased SST and zooplankton biomass in the western North Pacific. The reverse occurs with a weakened Aleutian Low. With an increase in catch after 1989, the body weight of adult pink salmon increased, suggesting that the carrying capacity of the western North Pacific Ocean for this stock has since increased.

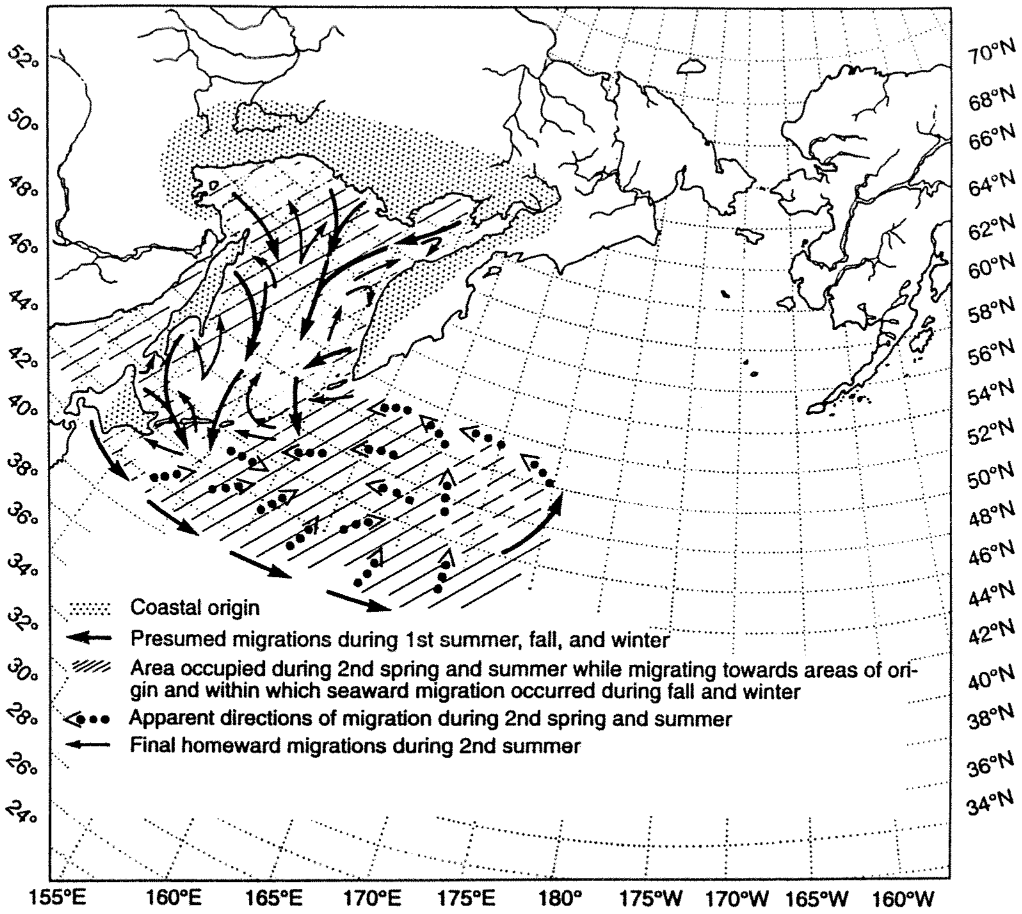
INTRODUCTION

There has been increasing evidence that long-term production trends of Pacific salmon (*Oncorhynchus* spp.) are related to climate change (Beamish 1993; Beamish and Bouillon 1993; Francis and Hare 1994; Hare and Francis 1995; Beamish et al. 1995, 1997b, 1997c, 1999a, 1999b; Brodeur and Ware 1995; Klyashtorin and Smirnov 1995; Adkinson et al. 1996; Gargett 1997; Klyashtorin 1997; Mantua et al. 1997; Francis et al. 1998; Downton and Miller 1998). However, most of the studies deal with the stocks of salmon in North America or total catches in the whole North Pacific, and there are few studies focusing on the salmon production in Asia related to climate (Krovnin 1998). Large-scale climate change is indeed thought to have widely affected salmon production in the North Pacific Ocean (Beamish and Bouillon 1993; Klyashtorin and Smirnov 1995; Klyashtorin 1997; Beamish et al. 1999b). Its influence, however, may differ between North American and Asian salmon stocks as the stocks use different oceanic regions for growth (especially in the early ocean life histories), although high-seas distributions overlap, and each region has its own oceanographic conditions and biological production. It may be that Asian salmon in the western North Pacific show different climate-related production patterns from North American salmon. Moreover, there is little information on the mechanisms linking climate change to salmon production. We need more information on the whole scenario from the climate through the ocean environment (including water temperature and zooplankton) to salmon production.

East Sakhalin pink salmon (*O. gorbuscha*) are one of the biggest stocks of Pacific salmon in Asia with catch exceeding 100,000 metric tonnes in 1991. The species is distributed as juveniles in the Okhotsk Sea from summer to autumn and occurs as immature and maturing fish in the western North Pacific Ocean in winter and spring (Fig. 1) (Takagi et al. 1981; Shuntov 1994). Studying this stock enables us to evaluate the effects of changes in the climate and ocean environment off Far East Asia on a local Asian stock. In the present paper, I examine data collected largely from the early 1950s to the early 1990s to relate production trends of East Sakhalin pink salmon to long-term changes in the climate and ocean environment in the Okhotsk Sea and western North Pacific. Specifically, since it is known that two climatic

All correspondence should be addressed to K. Nagasawa.
e-mail: ornatus@ss.enyo.affrc.go.jp

Fig. 1. Distribution and migration of Far Eastern Asian pink salmon, including East Sakhalin stock [from Heard (1991) who modified Fig. 94 in Takagi et al. (1981), with the permission of the University of British Columbia Press].



regime shifts occurred in 1977 and 1989 (Beamish et al. 1997a, 1997b), I focus on fluctuations in stock of East Sakhalin pink salmon in relation to these regime shifts. I also relate annual changes in body size to the stock size to infer shifts in ocean carrying capacity for pink salmon.

MATERIALS AND METHODS

Pink Salmon Data

Data on East Sakhalin pink salmon used in this paper were provided to the Government of Japan by the Government of the Soviet Union and currently the Government of the Russian Federation. Annual catch data during the period from 1952 to 1997 included those of pink salmon from West Sakhalin and the Kuril Islands, but as catches in these areas were low and their exact values were unknown, the non-corrected data were used as catch data for East Sakhalin pink salmon. Data on the number of pink salmon annually caught from 1958 to 1993 were also used. Data on the annual mean body weight of East Sakhalin pink salmon were based on the measurements of adult fish that had returned to their spawning rivers in July from 1958 to 1993 (excluding 1976 and 1984 when no data were available).

Climate Data

The Aleutian Low pressure system dominates the climate of the northern North Pacific Ocean from late in the year to the spring of the next year. For winters and springs of 1899–1990, Beamish and Bouillon (1993) calculated the area (square kilometers) of the North Pacific Ocean covered by the Aleutian Low pressure system less than 100.5 kPa. They used the sum of the winter and spring Aleutian Low values as an index of historical weather over the North Pacific Ocean and called it the Aleutian Low Pressure Index (ALPI). In the present study, data on the winter (January to March) ALPI anomaly from 1949 through 1997 were obtained from an appendix table in Beamish et al. (1997b), and 4-year running means were calculated to compare with the catch of East Sakhalin pink salmon and the sea surface temperature (SST) and zooplankton biomass in the western North Pacific Ocean.

Sea Ice Area Data

As SST and zooplankton biomass data in the Okhotsk Sea were not available for the present study, data on sea ice area were used as an index of the ocean environment. Part of the Okhotsk Sea is covered with sea ice during the winter (Aota and Ishikawa 1993). Annual data on accumulated sea ice concentration in the Okhotsk Sea south of 50°N from the period 1969–1992 were taken from Fig. 13 in Aota and Ishikawa (1993), and 4-year running means were calculated. The accumulated sea ice concentration was defined as the sum of daily percentages of a survey area covered with sea ice from January 1 to May 31 of each year (Aota and Ishikawa 1993).

Sea Surface Temperature Data

SST data in the western North Pacific Ocean were provided by Dr. K. Tadokoro (National Research Institute of Far Seas Fisheries, present address: Ocean Research Institute, University of Tokyo). He analyzed the SST data taken from 1961 to 1990 in an oceanic area (the Oyashio region, see below for definition) from the east coast of northern Honshu and Hokkaido to 145°E and from 40°N to 43°N. In the present paper, annual values of 48-month running means were used.

Zooplankton Biomass Data

Zooplankton biomass data used in this study were taken from Fig. 12 in Odate (1994). Based on 17,242 zooplankton samples collected in the western North Pacific off the east coast of Tohoku, Japan from 1951 to 1990, this author showed long-term changes in zooplankton biomass in three regions (i.e., the Kuroshio, Oyashio, and Kuroshio-Oyashio transition regions). The Oyashio region was defined as waters less than 5°C at 100 m in depth (Odate 1994), and the zooplankton biomass data in this region were used in the present study. The gear used for zooplankton sampling was a MARUTOKU net (net opening 0.45 m, net length 0.80 m, and mesh size 0.33 mm), which was vertically towed from 150 m in wire length (not depth) to the surface. The zooplankton collected was fixed in formalin on board and brought to the laboratory, where necessary sorting was done and the wet weight was measured. The zooplankton biomass was defined as the wet weight (g) of zooplankton per surface square meter, excluding large juvenile fish and gelatinous zooplankton (Odate 1994). In the present paper, annual values of 48-month running means of the zooplankton biomass were used.

RESULTS

Changes in Catch and Body Weight of East Sakhalin Pink Salmon

East Sakhalin pink salmon were commercially caught on the high seas of the western North Pacific by Japanese salmon fisheries until 1976 (Fig. 2). The 200-mile exclusive economic zone was established in 1977, when the Japanese high-seas fisheries ended. Despite this absence of fisheries, East Sakhalin pink salmon catch began to decrease in 1978 and remained low until 1988 (Fig. 2). Catch sharply increased in 1989 and thereafter, the highest ever recorded catch occurring in 1991.

The annual mean body weight of both male and female adult pink salmon showed similar trends in relation to catch fluctuations (Fig. 2). With increasing catch from the late 1960s to 1977, body weight declined. During the period from 1978 to 1988 when catch decreased, body weight remained low. In 1989 and afterward, catch increased and body weight was higher than that recorded from 1977 to 1988.

There is a negative relationship between annual catch number of pink salmon and annual mean body weight of adult fish (Fig. 3): in years when catch was high (low), the body weight was low (high). The relationship for the period from 1989 to 1993 was different from that for 1958 through 1988.

Changes in ALPI over the North Pacific and Sea Ice Area in the Okhotsk Sea

The ALPI increased in the 1970s and peaked in 1979 (Fig. 4). Subsequently, the ALPI decreased in the 1980s but remained at a high level from 1977 to 1987. This indicates that the intensity of the Aleutian Low strengthened during this period.

Annual changes in sea ice area showed similar trends to those of ALPI (Fig. 4). Sea ice area in the southern Okhotsk Sea steadily began to increase in 1975 and peaked in 1978. Although sea ice area was at an intermediate level from 1982 to 1985, it remained relatively high until 1988. Sea ice area abruptly decreased in 1989 and 1990.

Changes in SST and Zooplankton Biomass in the Western North Pacific

SST in the Oyashio region of the western North Pacific was relatively high from the mid-1960s to the early 1970s (Fig. 5). It decreased irregularly from 1971 to 1983, remained low until 1989, and increased sharply in 1990.

Fig. 2. Annual changes in catch (top) and body weight (bottom) of pink salmon along East Sakhalin, Russia, from the 1950s to 1990s. The regime shifts of 1977 and 1989 are indicated by vertical lines. A horizontal bar indicates the period of Japanese high-seas salmon fisheries from 1952 to 1976.

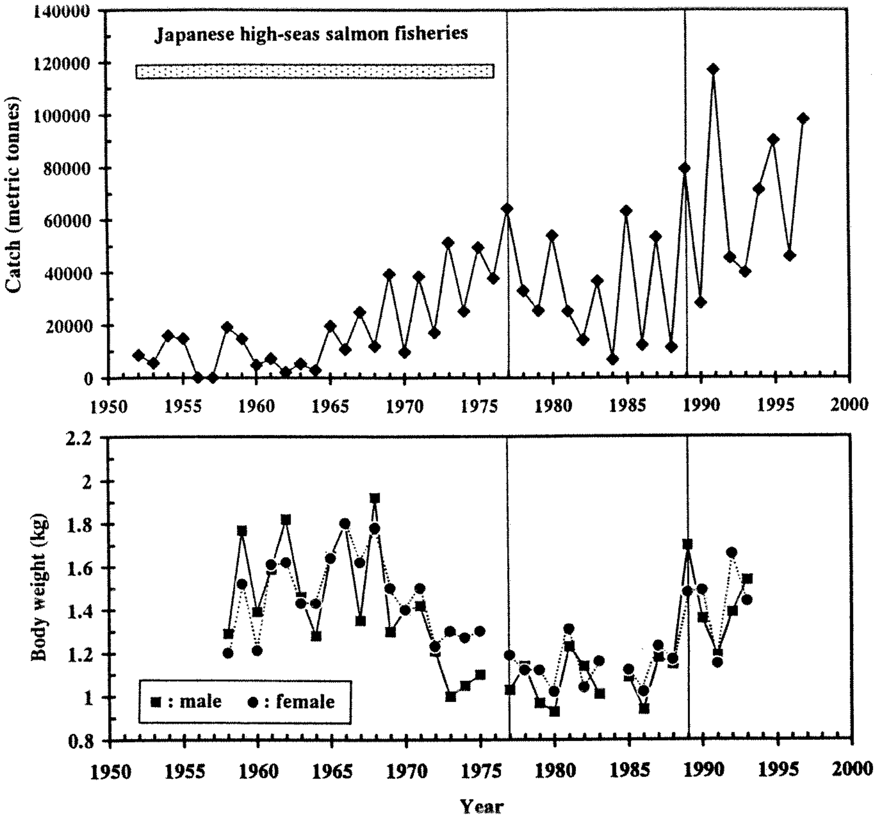


Fig. 3. Relationship between body weight of male (top) and female (bottom) adult pink salmon and catch number along East Sakhalin from 1958 to 1993.

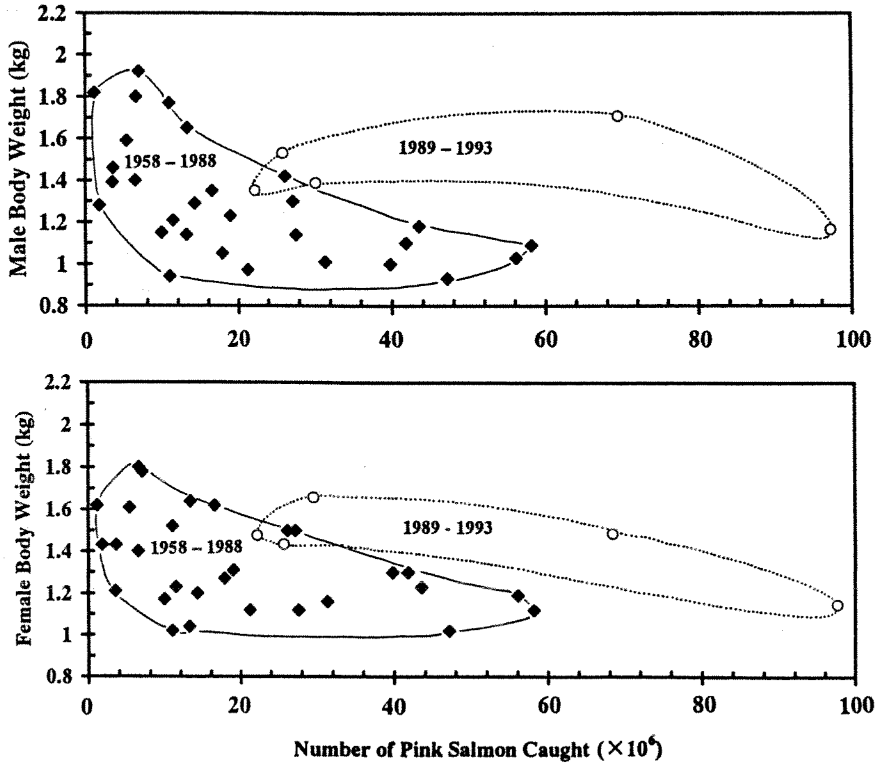


Fig. 4. Long-term changes in winter Aleutian Low Pressure Index (ALPI) anomaly over the North Pacific (top) and accumulated sea ice concentration in southern Okhotsk Sea south of 50°N (bottom). The regime shifts of 1977 and 1989 are indicated by vertical lines.

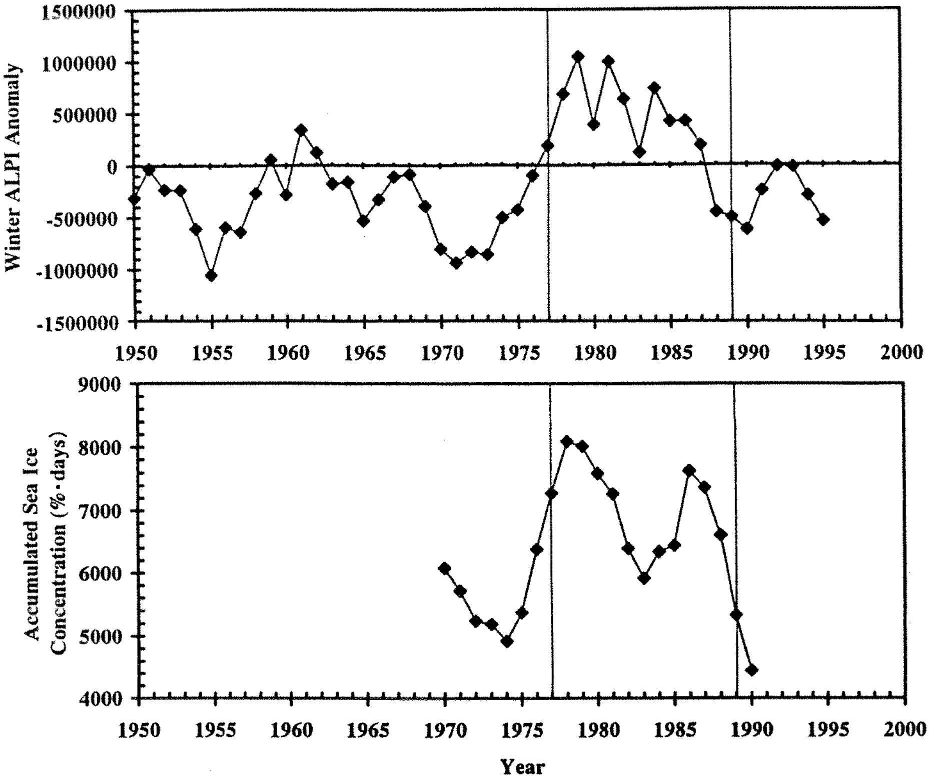
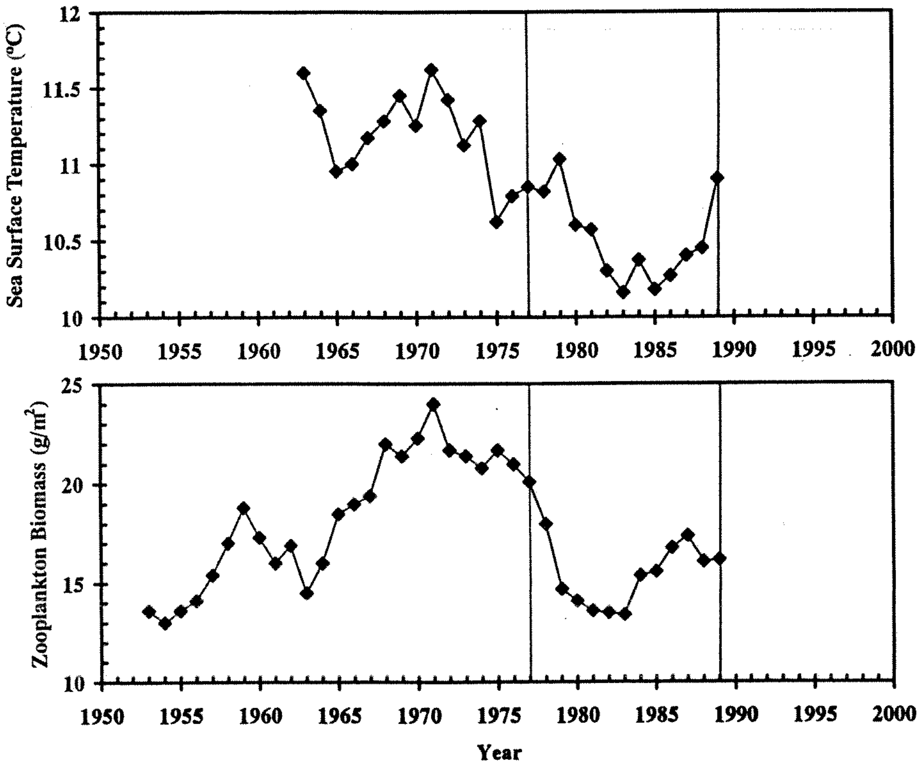


Fig. 5. Long-term changes in sea surface temperature (top) and zooplankton biomass (bottom) in the Oyashio region of the western North Pacific. The regime shifts of 1977 and 1989 are indicated by vertical lines.



Annual changes in zooplankton biomass in the Oyashio region were similar to those in SST (Fig. 5). While zooplankton biomass was high from the mid-1960s to the mid-1970s, it declined sharply in 1978 and remained low thereafter.

DISCUSSION

The present study shows that catch trends in East Sakhalin pink salmon were closely related to changes in the climate and ocean environment in the Okhotsk Sea and western North Pacific Ocean. Through the mid-1970s to the late 1980s when the Aleutian Low intensified, sea ice area expanded in the Okhotsk Sea, both SST and zooplankton biomass remained low in the western North Pacific, and pink salmon catch in East Sakhalin declined in spite of the disappearance of Japanese high-seas salmon fisheries. However, after 1989 when the intensity of the Aleutian Low weakened, sea ice area sharply decreased in the Okhotsk Sea, and East pink salmon catch dramatically increased, although corresponding SST and zooplankton data were not unfortunately demonstrated for the western North Pacific. These relationships imply that weakening of the Aleutian Low provides favorable ocean environments for pink salmon in the Okhotsk Sea and western North Pacific.

East Sakhalin pink salmon stay as juveniles in the Okhotsk Sea from summer to autumn before migrating to the western North Pacific in early winter (Takagi et al. 1981; Shuntov 1994). An extensive winter sea ice cover is thought to delay an increase in SST in the Okhotsk Sea in spring and early summer. This would create unfavorable conditions for juvenile pink salmon. Shershnev and Chupakin (1992) showed that higher returns of Northeast Sakhalin pink salmon are closely associated with higher coastal June–July SST. During the period when the Okhotsk Sea is widely covered with sea ice, decreased SST (and possibly decreased biological production) may induce a high mortality of juvenile pink salmon. The expansion of sea ice area in the Okhotsk Sea has a close relationship with intensifying of the Aleutian Low (Parkinson 1990; Tachibana et al. 1996). In years when the Aleutian Low is strong, winter northwest winds bring cold air from Siberia, which enhances the formation and movement of sea ice in the Okhotsk Sea. The abrupt decrease in sea ice cover in this sea corresponded well to the weakening of the Aleutian Low in 1989 (Tachibana et al. 1996). Therefore, the production of East Sakhalin pink salmon may be indirectly controlled by annual changes in the intensity of the Aleutian Low over the North Pacific.

The present study also shows that long-term trends in pink salmon catch are closely related to the marine environment in the western North Pacific, where immature and maturing pink salmon reside from winter to spring. This implies that SST and zooplankton biomass in the western North Pacific are responsible for the survival or mortality of pink salmon. From this viewpoint, one possible explanation for low catches of pink salmon during the period of the intensified Aleutian Low is lower survival of overwintering fish owing to decreased SST and zooplankton biomass in the western North Pacific. Specifically, as winter zooplankton biomass remains at a low level (about 10% of the summer biomass) in the western North Pacific (Nagasawa this volume), overwintering salmon appear to survive under very poor food conditions. In addition, Blackbourn (1993) suggested that temperatures experienced by maturing adult salmon may affect the development of eggs or sperm and the subsequent survival rate of the eggs and fry in fresh water. If this is true, another possible explanation is that colder ocean temperatures in the western North Pacific during the period of the intense Aleutian Low reduce the survival of eggs and fry, leading to the low production of pink salmon.

Note that East Sakhalin pink salmon decreased from the mid-1970s to the late 1980s, while during this period the production of northern North American (Alaskan) stocks increased (Beamish 1993; Beamish and Bouillon 1993; Francis and Hare 1994; Hare and Francis 1995; Klyashtorin and Smirnov 1995; Beamish et al. 1997a, 1999b; Klyashtorin 1997; Mantua et al. 1997; Francis et al. 1998; Downton and Miller 1998). Stocks on southern North America (southern British Colombia, Washington, Oregon, California) showed decreasing trends during this period (Beamish et al. 1995, 1997a, 1999a). The reason why East Sakhalin pink salmon exhibited opposite production trends from northern North American stocks but similar trends to southern North American stocks is at least partly that a climate change (the Aleutian Low in the present study) causes different oceanographic changes among various regions of the North Pacific and adjacent seas. An abrupt shift in the North Pacific climate, including intensifying of the winter Aleutian Low, began in the winter of 1976–1977 (Miller et al. 1994; Graham 1994). This shift led to weather changes in various regions of the North Pacific Ocean (Nitta and Yamada 1989; Trenberth 1990; Trenberth and Hurrel 1995; Minobe 1997; Yasuda and Hanawa 1997; Kachi and Nitta 1997; Nakamura et al. 1997; Mantua et al. 1997; Minobe and Mantua 1999). The shift also resulted in changes in the ocean environment and biological production (Venrick et al. 1987; Ebbesmeyer et al. 1991; Tanimoto et al. 1993; Polovina et al. 1995; Hayward 1997; Sugimoto and Tadokoro 1997, 1998; McGowan et al. 1998). After the climatic regime shift in the mid-1970s, anomalous northerly winds on the one hand increased mixing and horizontal advection, and resulted in cooling in the central and western North Pacific (Miller et al.

1994). In the Gulf of Alaska on the other hand, warm moist air was brought from the south, warming the coastal ocean (Mantua et al. 1997). Both SST and zooplankton biomass increased in the Gulf of Alaska after the mid-1970s (McFarlane and Beamish 1992). Brodeur and Ware (1992) and Brodeur et al. (1996) also found that zooplankton biomass in the Gulf of Alaska doubled between the two periods (1952–1962 and 1980–1988). These observations were opposite to the decreasing trends in SST and zooplankton biomass found in the western North Pacific (present study). The regional differences in response of the ocean environment to climate change may result in regional differences in salmon survival and production. When we analyze relationships between long-term shifts in salmon production and climate/ocean environment, we need to study the relationships at both regional and whole North Pacific scales.

The catch of East pink salmon was extremely high after 1989, and the body weight of adult pink salmon was also greater after 1989 than that recorded from 1958 to 1988. It is well known that there is a population density-dependent effect in species of Pacific salmon: when salmon are abundant, their body size is smaller, and *vice versa* (Ishida et al. 1993; Helle and Hoffman 1995; Kaeriyama 1999). If this is the case, the body weight of East Sakhalin pink salmon should have decreased after 1989 with increasing abundance. However, the results found in the present study were opposite, suggesting that the ocean's carrying capacity for East Sakhalin pink salmon improved after 1989.

For future work, it is necessary to analyze details of relationships between the climate/ocean environments in the Okhotsk Sea and catches of stocks of Far Eastern Asian salmon. Many commercially important salmon stocks of Russia and Japan, including East Sakhalin pink salmon, utilize the Okhotsk Sea, and information linking long-term changes in salmon stocks to the climate/ocean environments is essential for efficient fisheries management. With global warming, air temperature is expected to dramatically increase in the 21st century over the Okhotsk Sea (cf. Wakatsuchi 1996), and changes in the ocean environment and related biological production should therefore be monitored carefully.

ACKNOWLEDGEMENTS

I thank Yukimasa Ishida (Hokkaido National Fisheries Research Institute, Kushiro) and Masahide Kaeriyama (Hokkaido Tokai University, Sapporo) for their encouragement and discussion during this study. Thanks also to Kazuaki Tadokoro (Ocean Research Institute, University of Tokyo) for providing the SST data. I am grateful to David W. Welch (Pacific Biological Station, Department of Fisheries and Oceans, Nanaimo) and Tomowo Watanabe (National Research Institute of Far Seas Fisheries, Shimizu) for their help with the literature.

REFERENCES

Adkinson, M.D., R.M. Peterman, M.F. Lapointe, D.M. Gillis, and J. Korman. 1996. Alternative models of climatic effects on sockeye salmon (*Oncorhynchus nerka*) productivity in Bristol Bay, Alaska and Fraser River, British Columbia. Fish. Oceanogr. 5: 137–152.

Aota, M., and M. Ishikawa. 1993. Data on the variation in ice concentration along the Okhotsk Sea coast of Hokkaido. Sea and Sky 69: 33–46. (In Japanese with English abstract).

Beamish, R.J. 1993. Climate and exceptional fish production off the west coast of North America. Can. J. Fish. Aquat. Sci. 50: 2270–2291.

Beamish, R.J., and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Can. J. Fish. Aquat. Sci. 50: 1002–1016.

Beamish, R.J., B.E. Riddell, C.-E.M. Neville, B.L. Thompson, and Z. Zhang. 1995. Declines in chinook salmon catches in the Strait of Georgia in relation to shifts in the marine environment. Fish. Oceanogr. 4: 243–256.

Beamish, R.J., C. Mahnken, and C.M. Neville. 1997a. Hatchery and wild production of Pacific salmon in relation to large-scale, natural shifts in the productivity of the marine environment. ICES J. Mar. Sci. 54: 1200–1215.

Beamish, R.J., G.A. McFarlane, D. Noakes, M. Folkes, V.V. Ivanov, and V. Kurashov. 1997b. A comparison of the Aleutian Low Pressure Index and the Atmospheric Circulation Index as indices of Pacific salmon abundance trends. (NPAFC Doc. 289). 25p. Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, B.C., Canada V9R 5K6.

Beamish, R.J., C.-E.M. Neville, and A.J. Cass. 1997c. Production of Fraser River sockeye salmon (*Oncorhynchus nerka*) in relation to decadal-scale changes in the climate and the ocean. Can. J. Fish. Aquat. Sci. 54: 543–554.

Beamish, R.J., G.A. McFarlane, and R.E. Thomson. 1999a. Recent declines in the recreational catch of coho salmon (*Oncorhynchus kisutch*) in the Strait of Georgia are related to climate. Can. J. Fish. Aquat. Sci. 56: 506–515.

Beamish, R.J., D.J. Noakes, G.A. McFarlane, L. Klyashtorin, V.V. Ivanov, and V. Kurashov. 1999b. The regime concept and natural trends in the production of Pacific salmon. Can. J. Fish. Aquat. Sci. 56: 516–526.

Blackbourn, D.J. 1993. Sea surface temperature and the subsequent freshwater survival rate of some salmon stocks: a surprising link between the climate of land and sea. *In* Proceedings of 9th Annual Pacific Climate (PACLIM) Workshop, April 21–24, 1992. *Edited by* K.T. Redmond and V.L. Tharp. California Department of Water Resources. Interagency Ecological Studies Program. Tech. Rep. No. 34: 23–32.

Brodeur, R.D., and D.M. Ware. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fish. Oceanogr. 1: 32–38.

Brodeur, R.D., and D.M. Ware. 1995. Interdecadal variability in distribution and catch rates of epipelagic nekton in the Northeast Pacific Ocean. *In* Climate Change and Northern Fish Populations. *Edited by* R.J. Beamish. Can. Sp. Pub. Fish. Aquat. Sci. No. 121. pp. 329–356.

Brodeur, R.D., B.W. Frost, S.R. Hare, R.C. Francis, and W.J. Ingraham Jr. 1996. Interannual variations in zooplankton biomass in the Gulf of Alaska, and covariation with California Current zooplankton biomass. Calif. Coop. Oceanic Fish. Invest. Rep. 37: 80–98.

Downton, M.W., and K.A. Miller. 1998. Relationships between Alaskan salmon catch and North Pacific climate on interannual and interdecadal time scales. Can. J. Fish. Aquat. Sci. 55: 2255–2265.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McLain, F.H. Nichols, D.H. Peterson, and K.T. Redmond. 1991. 1976 step in the Pacific climate: forty environmental changes between 1968–1975 and 1977–1984. *In* Proceedings of 7th Annual Pacific Climate (PACLIM) Workshop, April 1990. *Edited by* J.L. Betancourt and V.L. Tharp. California Department of Water Resources. Interagency Ecological Studies Program. Tech. Rep. No. 26: 115–141.

Francis, R.C., and S.R. Hare. 1994. Decadal-scale regime shifts in the large marine ecosystems of the North-east Pacific: a case for historical science. Fish. Oceanogr. 3: 279–291.

Francis, R.C., S.R. Hare, A.B. Hollowed, and W.S. Wooster. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. Fish. Oceanogr. 7: 1–21.

Gargett, A.E. 1997. The optimal stability 'window': a mechanism underlying decadal fluctuations in North Pacific salmon stocks? Fish. Oceanogr. 6: 109–117.

Graham, N.E. 1994. Decadal scale variability in the 1970s and 1980s: observations and model results. Clim. Dyn. 10: 135–162.

Hare, S.R., and R.C. Francis. 1995. Climate change and salmon production in the Northeast Pacific Ocean. *In* Climate Change and Northern Fish Populations. *Edited by* R.J. Beamish. Can. Sp. Pub. Fish. Aquat. Sci. No. 121: 357–372.

Hayward T.L. 1997. Pacific ocean climate change: atmospheric forcing, ocean circulation and ecosystem response. Tree 12: 150–154.

Heard, W.R. 1991. Life history of pink salmon (*Oncorhynchus gorbuscha*). *In* Pacific Salmon Life Histories. *Edited by* C. Groot and L. Margolis. UBC Press, Vancouver. pp. 119–230.

Helle, J.H., and M.S. Hoffman. 1995. Size decline and older age at maturity of two chum salmon (*Oncorhynchus keta*) stocks in western North America, 1972–92. *In* Climate Change and Northern Fish Populations. *Edited by* R.J. Beamish. Can. Sp. Pub. Fish. Aquat. Sci. No. 121: 245–260.

Ishida, Y., S. Ito, M. Kaeriyama, S. McKinnell, and K. Nagasawa. 1993. Recent changes in age and size of chum salmon (*Oncorhynchus keta*) in the North Pacific Ocean and possible causes. Can. J. Fish. Aquat. Sci. 50: 290–295.

Kachi, M., and T. Nitta. 1997. Decadal variations of the global atmosphere-ocean system. J. Meteor. Soc. Japan 75: 657–675.

Kaeriyama, M. 1999. Hatchery programmes and stock management of salmonid populations in Japan. *In* Stock Enhancement and Sea Ranching. *Edited by* B.R. Howell, E. Moksness, and T. Svåsand. Fishing News Books, Oxford. pp. 153–167.

Klyashtorin, L. 1997. Global climate cycles and Pacific forage fish stock fluctuations. *In* Proceedings of the International Symposium on the Role of Forage Fishes in Marine Ecosystems. Alaska Sea Grant College Program Report No. 97–01. Univ. Alaska Fairbanks. pp. 545–557.

Klyashtorin, L., and B. Smirnov. 1995. Climate-dependent salmon and sardine stock fluctuations in the North Pacific. *In* Climate Change and Northern Fish Populations. *Edited by* R.J. Beamish. Can. Sp. Pub. Fish. Aquat. Sci. No. 121: 687–689.

Krovnin, A.S. 1998. Changes in abundance of Far East pink salmon (*Oncorhynchus gorbuscha*) stocks in the context of climatic variability in the North Pacific region. N. Pac. Anadr. Fish. Comm. Tech. Rep.: 14–15.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc. 78: 1069–1079.

McFarlane, G.A., and R.J. Beamish. 1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 49: 743–753.

McGowan, J.A., D.R. Cayan, and L.M. Dorman. 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific. Science 281: 210–217.

Miller, A.J., D.R. Cayan, T.P. Barnett, N.E. Graham, and J.M. Oberhuber. 1994. The 1976–1977 climate shift of the Pacific Ocean. Oceanography 7: 21–26.

Minobe, S. 1997. A 50–70 year climatic oscillation over the North Pacific and North America. Geophys. Res. Lett. 24: 683–686.

Minobe, S., and N.J. Mantua. 1999. Interdecadal modulation of interannual atomospheric and oceanic variability over the North Pacific. Prog. Oceanogr. 43: 163–192.

Nagasawa, K. This volume. Winter zooplankton biomass in the subarctic North Pacific, with a discussion on the overwintering survival strategy of Pacific salmon (*Oncorhynchus* spp.). N. Pac. Anadr. Fish. Comm. Bull. No. 2.

Nakamura, H., G. Lin, and T. Yamagata. 1997. Decadal climate variability in the North Pacific during the recent decades. Bull. Amer. Meteor. Soc. 98: 2215–2225.

Nitta, T., and S. Yamada. 1989. Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation. J. Meteor. Soc. Japan 67: 375–383.

Odate, K. 1994. Zooplankton biomass and its long-term variation in the western North Pacific Ocean, Tohoku Sea Area, Japan. Bull. Tohoku Nat. Fish. Res. Inst. No. 56: 115–173. (In Japanese with English abstract).

Parkinson, C.L. 1990. The impact of the Siberian high and Aleutian low on the sea ice cover of the Sea of the Okhotsk. Ann. Glacial. 14: 226–229.

Polovina, J.J., G.T. Mitchum, and G.T. Evans. 1995. Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the Central and North Pacific, 1960–88. Deep-Sea Res. 42: 1701–1716.

Shershnev, A.A., and V.M. Chupakin. 1992. The study of Pacific salmon in Sakhalin and the Southern Kuriles. *In* Proceedings of the International Workshop on Future Salmon Research in the North Pacific Ocean. *Edited by* Y. Ishida, K. Nagasawa, D.W. Welch, and A.P. Shershnev. National Research Institute of Far Seas Fisheries, Shimizu. pp. 19–21.

Shuntov, V.P. 1994. New data about marine life of Asian pink salmon. Izv. TINRO 116: 3–41. (In Russian with English abstract).

Sugimoto, T., and K. Tadokoro. 1997. Interannual-interdecadal variations in zooplankton biomass, chlorophyll concentration and physical environment in the subarctic Pacific and Bering Sea. Fish. Oceanogr. 6: 74–93.

Sugimoto, T., and K. Tadokoro. 1998. Interdecadal variations of zooplankton biomass and physical environment in the North Pacific. Fish. Oceanogr. 7: 289–299.

Tachibana, Y., M. Honda, and K. Takeuchi. 1996. The abrupt decrease of the sea ice over the southern part of the Sea of Okhotsk in 1989 and its relation to the recent weakening of the Aleutian Low. J. Meteor. Soc. Japan 74: 579–584.

Takagi, K., K.V. Aro, A.C. Hartt, and M.B. Dell. 1981. Distribution and origin of pink salmon (*Oncorhynchus gorbuscha*) in offshore waters of the North Pacific Ocean. Int. North Pac. Fish. Comm. Bull. No. 40.

Tanimoto, Y., N. Iwasaka, K. Hanawa, and Y. Toba. 1993. Characteristic variations of sea surface temperature with multiple time scales in the North Pacific. J. Climate 6: 1153–1160.

Trenberth, K.E. 1990. Recent observed interdecadal climate changes in the Northern Hemisphere. Bull. Amer. Meteor. Soc. 71: 988–993.

Trenberth, K.E., and J.W. Hurrell. 1995. Decadal coupled atmosphere-ocean variations in the North Pacific Ocean. *In* Climate Change and Northern Fish Populations. *Edited by* R.J. Beamish. Can. Sp. Pub. Fish. Aquat. Sci. No. 121: 15–24.

Venrick, E.L., J.A. McGowan, D.A. Cayan, and T.L. Hayward. 1987. Climate and chlorophyll *a* long-term trends in the central North Pacific Ocean. Science 238: 70–72.

Wakatsuchi, M. 1996. Perspective of research on the Okhotsk Sea. Kaiyo Monthly 28: 523–526. (In Japanese).

Yasuda, T., and K. Hanawa. 1997. Decadal changes in the mode waters in the midlatitude North Pacific. J. Phys. Oceanogr. 27: 858–870.