Influence of Sea Ice on Spring Phytoplankton Production and Foraging Period of Juvenile Salmon in Nemuro Strait

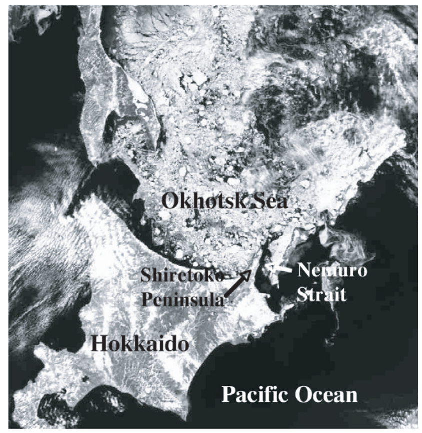
Ikutaro Shimizu, Toshihiko Saito and **Jiro Seki**

Research Division, National Salmon Resources Center, Fisheries Research Agency
2-2 Nakanoshima, Toyohira-ku, Sapporo 062-0922, Japan

Keywords: Okhotsk Sea, Nemuro Strait, sea ice, spring bloom, juvenile salmon

The Okhotsk Sea is an important summer nursery for Japanese juvenile salmon (Mayama and Ishida 2003). Juvenile salmon migrate through coastal waters around Hokkaido to the Okhotsk Sea in the spring. They rear in the Okhotsk Sea through the summer and autumn, migrating to the Pacific Ocean for overwinter (Urawa et al. 2001). Sea ice dynamics influence the biological production of the Okhotsk Sea, thus are important to the growth and survival of juvenile salmon (Asami et al. 2005).

Fig. 1. Satellite image of the ice-covered Okhotsk Sea, showing the research area in Nemuro Strait. This NOAA image was produced by Kitami Institute of Technology.



Nemuro Strait, located along Shiretoko Peninsula and Kunashiri Island, eastern Hokkaido is a marginal sea of the southwestern Okhotsk Sea. The fisheries production in this strait is high and large salmon home to the waters around Nemuro Strait each year. Nemuro Strait is ice covered in the winter same as the Okhotsk Sea. There is considerable information on the relationship of sea ice to biological productivity in the Bering Sea (McRoy and Goering 1974; Alexander 1980; Schandelmeier and Alexander 1981; Alexander and Niebauer 1981; Niebauer and Alexander 1985; Niebauer et al. 1990; Niebauer 1995; Stabeno et al. 1998; Saitoh et al. 2002). There is little information on the relationship of sea ice and biological productivity in the Okhotsk Sea (Ohshima et al. 2001; Okunishi et al. 2005).

We investigated the Nemuro Strait to clarify the variability of spring biological production after the retreat of sea ice and the function of sea ice in coastal waters. Six sampling stations were located from 0.5 km to 8 km off Rausu and Shibetsu in northern Nemuro Strait (Fig. 1). Oceanographic observations were conducted on board the chartered vessels *Rausu maru* of Rausu Fisheries Cooperative Association and *Hakucho* of Shibetsu Fisheries Cooperative Association, between the period before sea ice reached the coasts of Nemuro Strait (January) and after sea ice retreated from Nemuro Strait (July), from 1998 to 2003. The observations under sea ice were conducted aboard the icebreaker *Teshio maru* of the Japan Coast Guard in 1999. Water temperature and salinity were measured with an Alec Memory STD. Transparency was measured with a Secchi disk. Water samples were collected from surface to a depth of 200 m (0 m, 5 m, 10 m, 20 m, 30 m, 50 m, 75 m, 100 m, 150 m, and 200 m) with a Rigo B sampler and filtered with a Whatman GF/F filter. Nutrients (nitrate, phosphate and silicate) concentrations were measured using spectrophotometers (Flow Injection Analyzer 5002 and Hitachi 100-60). The filters were extracted with 100% methyl alcohol (Otsuki et al. 1987) and chlorophyll a concentration measured with a Turner AU10 fluorometer. Accumulated ice concentration in the Okhotsk coastal area of Hokkaido was provided by the Sea Ice Laboratory of Hokkaido University, Mombetsu City.

Accumulated ice concentrations on the Okhotsk coast of Hokkaido were highest during 2000 and 2001, and lowest in 1998 (Fig. 2). However, sea ice retreated from the coastal waters in the middle of March in 1998, 2000 and 2001, one month earlier than 1999. Peak chlorophyll a concentrations in the surface layer (upper 10 m) off Shibetsu and Rausu occurred in the middle April of 1998, 2000 and 2001.

A chlorophyll a peak was not observed in 1999 during the retreat of the sea ice (Fig. 3). On the other hand, a strong phytoplankton bloom occurred in late March when sea ice began to retreat in 1998, 2000 and 2001. A mixed layer developed and a peak zooplankton biomass was observed in late June 2001 (Seki et al. 2006).

Nutrients and chlorophyll a concentrations were determined to examine the relationship between sea ice and the phytoplankton bloom in 1998 and 2003. Nutrients (nitrate, phosphate and silicate) concentrations in Nemuro Strait were higher during the period of ice cover than before or after. The concentrations of nitrogen, phosphorus and silica were 6.8 µmol/l, 0.9 µmol/l and 18.3 µmol/l, respectively before ice cover. During the period of ice cover, the concentrations of nitrogen, phosphorus and silica were 11.2 µmol/l, 1.0 µmol/l and 23.0 µmol/l, respectively. The ratio of nutrients in the water column under sea ice was similar to the Okhotsk Intermediate Cold Water (Maita

All correspondence should be addressed to I. Shimizu.
e-mail: ikutaro@affrc.go.jp

Fig. 2. Accumulated ice concentrations off the Okhotsk coast of Hokkaido in 1998–2001. The accumulated ice concentration indicates an extent (%) of coastal areas covered with sea ice for each year.

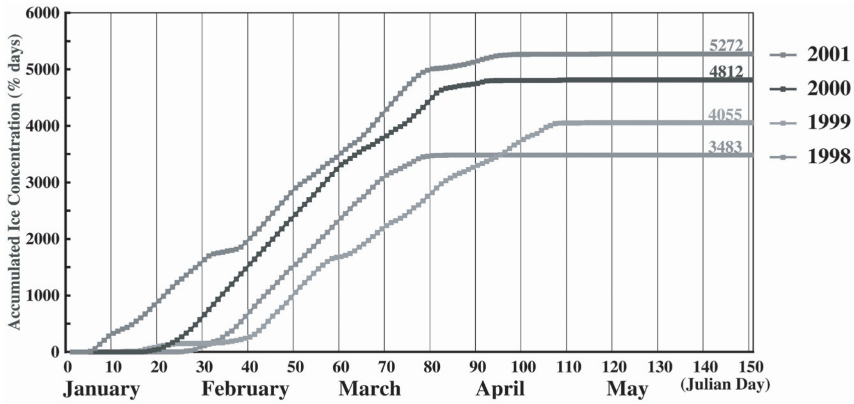
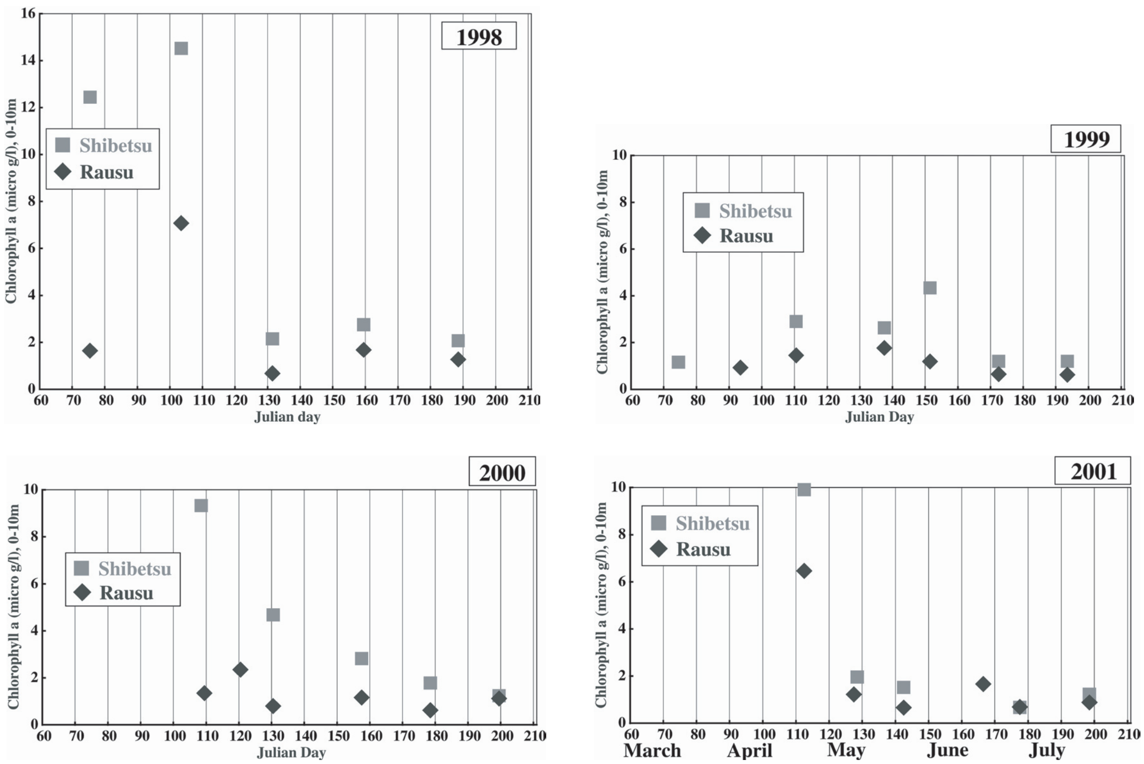


Fig. 3. Average concentrations of chlorophyll a in the surface layer (upper 10 m) off Shibetsu (west of Nemuro Strait) and Rausu (east of Nemuro Strait) after sea ice retreated in 1998–2001.



1986). After sea ice retreated nutrient concentrations decreased and chlorophyll a concentrations increased.

Volume of East Sakhalin Current Water was maximum between December and January (Itoh and Ohshima 2000; Itoh et al. 2003). It is believed that the water mass under sea ice originated from Okhotsk Intermediate Cold Water and brought high concentration of nutrients. These nutrients were utilized by phytoplankton blooms during the sea ice retreat period (Shimizu and Aota 2000).

Chlorophyll a concentrations were measured in northern Nemuro Strait during the 2002 sea ice retreat. Spring phytoplankton blooms were classified as ice edge bloom, open water bloom and under ice bloom. Ice edge phytoplankton blooms occurred in the salinocline formed during melting at the sea ice margin. Open water blooms occurred in the thermocline resulting from increased solar radiation and the rise of water temperature in open water after the sea ice retreat. In the Nemuro Strait, the ice edge bloom was larger than the open water bloom. The same was observed in the Okhotsk Sea during satellite remote sensing (Matsumoto et al. 2002).

The integrate value of the spring phytoplankton bloom differed among the years. A strong peak bloom occurred in 1998, but was not observed in 1999 (Fig. 4). The sea ice retreated in early March in 1998 and in late April in

Fig. 4. Vertical profiles of chlorophyll a at Rausu stations in Nemuro Strait on April 14, 1998 and April 21, 1999.

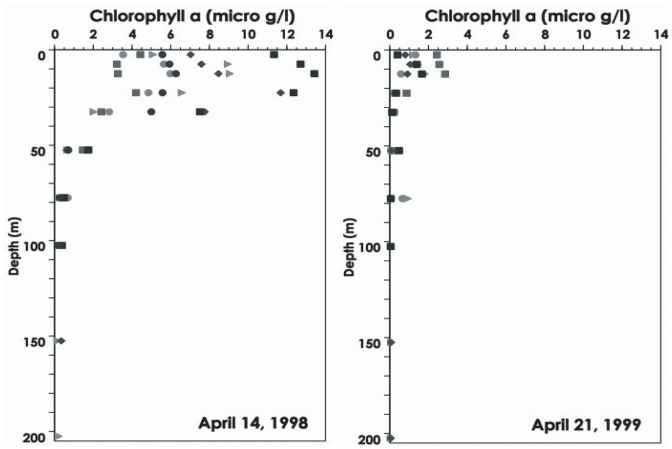


Fig. 5. Vertical profiles of sigma-t at Rausu stations in Nemuro Strait on April 14, 1998 and April 21, 1999.

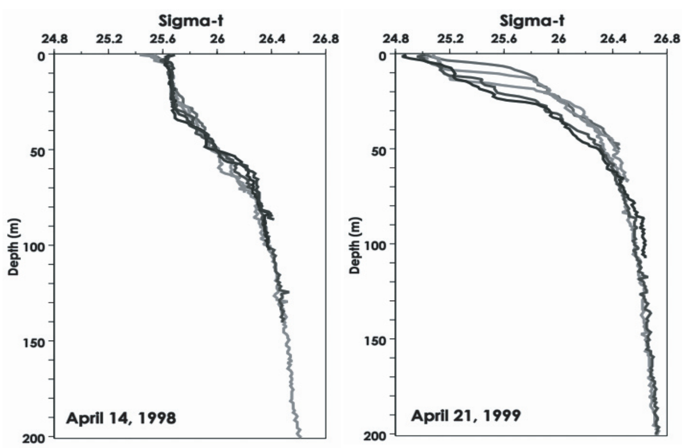
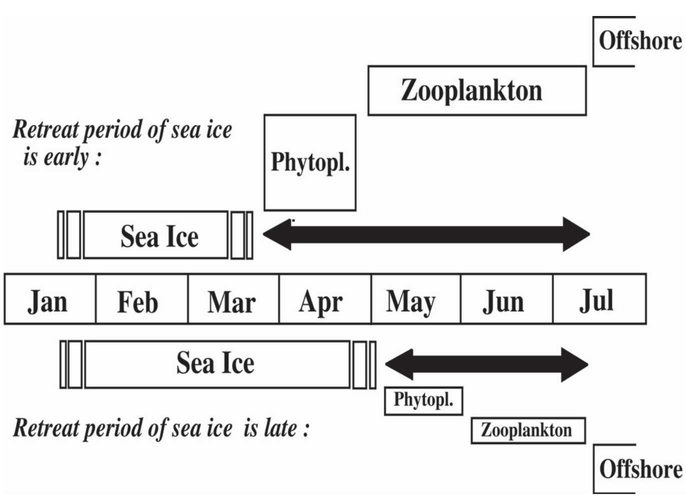


Fig. 6. Image of relation between retreat timing of sea ice and foraging period of salmon juveniles in the coastal waters of Nemuro Strait. The foraging period of salmon juveniles becomes longer and zooplankton biomass increases larger when sea ice retreats earlier.



1999, and the period of retreat was longer in 1999 than in 1998. The integrated value of the spring bloom was influenced by physical factors during the sea ice retreat period. The relationships between magnitude of the spring bloom and critical depth, nutrients, temperature and density were examined (Shimizu and Aota 1999; Shimizu et al. 2001). The surface density gradient (pycnocline) was more pronounced in 1999 than 1998, and the depth of the mixed layer was shallower in 1999 than 1998 (Fig. 5). Variation of density structure of a water mass triggered a phytoplankton bloom. This suggests that the thickness of the mixed layer influences the integrate value of the phytoplankton bloom after the sea ice retreats in Nemuro Strait.

In 1999, the nutrient concentrations in the water column in May were lower than in April. The decrease in silicate and nitrate was especially remarkable. Carbon content corresponding with the nutrient decrease in the periods from March to April in 1998 and April to May in 1999 was integrated using Redfield ratio (C:N:P = 106:16:1) and C: Chl.a ratio (= 30) (Strickland and Austin. 1960). Estimated value of chlorophyll a was 5.3 to 7.0 µg/l in 1998, about equal to the observed value of 6.97 µg/l. Estimated value of chlorophyll a in 1999 was 1.19 to 3.0 µg/l, also about equal to the observed value of 1.77 µg/l. The nutrients under sea ice were utilized by later production in 1999.

The coastal water mass observed in Nemuro Strait changed though the influence of Soya Warm Water between late June and middle July. Chum salmon juveniles also migrated from Nemuro Strait to the Okhotsk Sea in late June and middle July. The feeding period of juvenile salmon in the year when the retreat of sea ice was late, was shorter than in the year of short ice retreat period in Nemuro Strait (Fig. 6). On the other hand, in the southeastern Bering Sea, spring blooms occurred later in the cold water influenced by storms in the years when sea ice retreat was early (Hunt et al. 2002). Although our results differ from the hypothesis for the Bering Sea, they demonstrate that spring blooms were influenced by oceanographic conditions during the period of sea ice retreat. Nutrient value of secondary production was influenced by the primary production after sea ice retreat. That is to say, the magnitude of the phytoplankton bloom after sea ice retreat influences the biomass of the zooplankton community during the early ocean life of juvenile salmon.

REFERENCES

Alexander, V. 1980. Interrelationships between the seasonal sea ice and biological regimes. Cold Reg. Sci. Tech. 2: 157–178.

Alexander, V., and H.J. Niebauer. 1981. Oceanography of the eastern Bering Sea ice-edge zone in spring. Limnol. Oceanogr. 26 : 1111–1125.

Asami, H., H. Sato, H. Shimada, M. Sawada, Y. Miyakoshi, D. Ando and M. Nagata. 2005. Fluctuations of the Zooplankton Community during Early Ocean Life of Chum Salmon in the Coastal Waters of Eastern Hokkaido, Okhotsk Sea. N. Pac. Anadr. Fish Comm. Tech. Rep. 6: 54–56.

Itoh, M., and K.I. Ohshima. 2000. Seasonal Variations of Water Masses and Sea Level in The Southwestern Part of the Okhotsk Sea. J. Oceanogr. 56: 643–654.

Itoh, M., K.I. Ohshima, and M. Wakatsuchi. 2003. Distribution and formation of Okhotsk Sea Intermediate Water An analysis of isopycnal climatological data. J. Geophys. Res. 108 (C8) 14: 1–18.

Hunt Jr., G.L., P. Stabeno, G. Walters, E. Sinclair, R.D. Brodeur, J.M. Napp, and N.A. Bond. 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep Sea Res. II 49: 5821–5853.

Maita, Y. 1986. Chemistry of the Okhotsk Sea. Mar. Sci. Month. 188: 117–122.

Matsumoto, C., S. Saitoh, and M. Wakatsuchi. 2002. Interannual variability of spring bloom in the Okhotsk Sea and their relation to sea ice distribution. Abstracts of 25th Symposium on Polar Biology. p. 44.

Mayama, H., and Y. Ishida. 2003. Japanese studies on the early ocean life of juvenile salmon. N. Pac. Anadr. Fish Comm. Bull. 3: 41–67.

McRoy, C.P., and J.J. Goering. 1974. The influence of ice on the primary productivity of the Bering Sea. *In* Oceanography of the Bering Sea. *Edited by* D. W. Hood and E. J. Kelley. Institute of Marine Science, Fairbanks, AK. pp. 403–421.

Niebauer, H.J., and V. Alexander. 1985. Oceanographic frontal structure and biological production at an ice edge. Cont. Shelf Res. 4: 367–388.

Niebauer, H.J., V. Alexander, and S. Henrichs. 1990. Physical and biological oceanographic interaction in the spring bloom. J. Geophys. Res. 95 (C12): 22229–22241.

Niebauer, H.J., V. Alexander, and S. Henrichs. 1995. A time-series study of the spring bloom at the Bering Sea ice edge. I. Physical processes, chlorophyll and nutrient chemistry. Cont. Shelf Res. 15: 1859–1877.

Ohshima, K.I., G. Mizuta, M. Itoh, Y. Fukamachi, T. Watanabe, Y. Nabae, K. Suehiro, and M. Wakatsuchi. 2001. Winter oceanographic conditions in the southwestern part of the Okhotsk Sea and their relation to sea ice. J. Oceanogr. 57: 451–460.

Okunishi, T., M.J. Kishi, H. Tanaka, and T. Yamashita. 2005. An ecosystem modeling study of spatio-temporal variations of phytoplankton distribution in the Okhotsk Sea. Cont. Research 25: 1605–1628.

Otsuki, A., M. Watanabe, and K. Sugahara. 1987. Chlorophyll pigments in methanol extracts from ten axenic cultured diatoms and three green algae as determined by reverse phase hplc with fluorometric detection. J. Phycol. 23: 406–414.

Saitoh, S., T. Iida, and K. Sasaoka. 2002. A description of temporal and spatial variability in the Bering Sea spring phytoplankton blooms (1997–1999) using satellite multi-sensor remote sensing. Prog. Oceanogr. 55: 131–146.

Schandelmeier, L., and V. Alexander. 1981. An analysis of the influence of ice on spring phytoplankton population structure in the southeast Bering Sea. Limnol. Oceanogr. 26: 935–943.

Seki, J., T. Saito, and I. Shimizu. 2006. Temporal changes of vertical distribution of zooplankton communities during spring to early summer in the Nemuro Strait coastal waters off Shibetsu, eastern Hokkaido. Bull. Nat. Salmon Resources Center 9: 37–46.

Shimizu, I., and M. Aota. 1999. Changes of chlorophyll a concentration in the Nemuro region after sea ice covered period. Abstracts of 14th International Symposium on Okhotsk Sea and Sea Ice. pp. 24–27.

Shimizu, I., and M. Aota. 2000. Does sea ice bring high biological production in early Spring? Abstracts of 15th International Symposium on Okhotsk Sea and Sea Ice. pp. 273–277.

Shimizu, I., M. Aota, and S. Saitoh. 2001. The scale of a primary production caused by the change in the period of retreat and the area of sea ice. Abstracts of 16th International Symposium on Okhotsk Sea and Sea Ice. pp. 174–180.

Stabeno, P.J., J.D. Schumacher, R.F. Davis, and J.M. Napp. 1998. Under-ice observations of water column temperature, salinity and spring phytoplankton dynamics: Eastern Bering Sea shell. J. Mar. Res. 56: 239–255.

Strickland, J. D. H., and K. H. Austin. 1960. On the forms, balance and cycle of phosphorus observed in the coastal and oceanic waters of the northeastern Pacific. J. Fish. Res. Board. Can. 17: 337–345.

Urawa, S., Y. Ueno, Y. Ishida, L.W. Seeb, P. A. Crane, S. Abe, and N.D. Davis. 2001. A migration model of Japanese chum salmon during early ocean life. N. Pac. Anadr. Fish Comm. Tech. Rep. 2: 1–2.