Decreasing Area of Chum Salmon (Oncorhynchus keta) Distribution in the North Pacific in Summer 1982–2016

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**ABSTRACT**

The area of chum salmon (*Oncorhynchus keta*) distribution in the North Pacific in summer from 1982 to 2016 was annually estimated using sea surface temperature (SST). Long term trends of SST in the North Pacific in summer were positive except for the United States west coast area. The maximum positive trend was about 0.07°C/year. In summer, SST in the whole North Pacific, except for the United States west coast, was warming so that the southern limit of chum salmon distribution has shifted northward. The interannual change in area of chum salmon distribution in summer had a statistically significant negative trend (P<0.01) which was about -30000 km²/year to -40000 km²/year. It is found that the area of chum salmon distribution in the North Pacific in summer has decreased approximately 10% during the last 35 years.

**INTRODUCTION**

It is known that Pacific chum salmon (*Oncorhynchus keta*) is widely distributed in the North Pacific Ocean and adjacent waters. There are major fronts of the Subarctic Front (4°C isotherm at 100 m depth) and the Subarctic Boundary (34.0 PSU at 0 m) in the North Pacific (Favorite et al., 1976). The Transition Domain is the zone between the Subarctic Front and the Subarctic Boundary (Fig. 1(a)). There is a clear relationship between salmon distribution and physical factors (temperature and salinity) in the offshore waters of the North Pacific. The upper thermal limit has been shown to be 15.6°C and the lower thermal limit is 2.7°C and the upper halo-limit is 34.45 psu for chum salmon (Azumaya et al., 2007). Thus, the limit of the southern distribution of chum salmon is from the Transition Domain to around the Subarctic Boundary. Based on the influence of global warming of the SRES A1B scenario of IPCC on the salmon distribution using these thermal and halo-limits, the southern limit of chum salmon distribution in summer in 2050 will shift northward and the area of chum salmon distribution in 2050 will decrease by 83% compared to current values (Azumaya unpublished data).

Averaged sea surface temperature (SST) from 2007 to 2016 at Kushiro Hokkaido Japan was warmer than that from 1980 to 2010 ([http://hnf.fra.affrc.go.jp/suion/suionjoho.html#2](http://hnf.fra.affrc.go.jp/suion/suionjoho.html#2))(Fig. 1(a)). The anomalies from mean SST which was removed the seasonal change had a positive trend (Fig. 1(b)). There is a possibility that the area of chum salmon distribution has decreased with recent warming of SST. However, it is not clear how the distribution of chum salmon has changed from the past to the present. Thus, we examined the interannual change in the area of the chum salmon distribution in the North Pacific in summer from 1982 to 2016.
MATERIALS AND METHODS

The area that is enclosed by the upper thermal limit (15.6°C), the lower thermal limit (2.7°C) and the upper halo-limit (34.45) was assumed as the acceptable habitat of chum salmon according to the definition by Azumaya et al. (2007). They showed that in winter and spring, the southern limit of the chum salmon distribution in the North Pacific was dependent on the halo-limit and that in summer and autumn, the southern limit of chum salmon distribution was dependent on the thermal limit. Thus, in this study, the area of chum salmon distribution in summer (July, August and September) from 1982 to 2016 was estimated using the gridded sea surface temperature (gSST). The gSST data are based on NOAA High-resolution Blended Analysis of Daily SST Data Set (https://www.esrl.noaa.gov/psd/data/gridded/). The daily gSST data during 1982 to 2016 at 1/4° X1/4° grid points between 30°N and 65°N, 140°E and 120°W were averaged for each month in summer. The horizontal distributions of the long term trend were calculated for each month. Composite maps of gSST in the North Pacific from 1982 to 2000 (20th century) and 2001 to 2016 (21st century) were constructed to clarify the chum salmon distribution corresponding to SST variations.

To verify the salmon distribution and sea conditions, the data used were collected on board Japanese salmon research vessels in offshore waters of the North Pacific Ocean from 1982 to 2004. Salmon research vessels have observed SST at research operation site and used research-type gillnets and commercial-type gillnets. These observations of salmon in summer were conducted from June to July. We analyzed the data obtained by research-type gillnets because this gear is non selective (containing 10 different mesh sizes ranging from 48 to 157 mm; Takagi 1975). Data in Jun and July from the area 30°N to 65°N, 170°E to 180° were stratified by 1 degree latitude by 10 degree longitude areas. The density index (catch-per-unit effort, CPUE) in each grid was calculated as follows:

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\text{CPUE} = \frac{\text{total catch in number}}{\text{total effort (in 30 tans of gillnet)}}
\]

The densities of chum salmon and observed SST in each area were averaged for year, and a time series of them in area was estimated.

RESULTS AND DISCUSSIONS

Fig. 2 showed the time and space structure of the interannual variations of the observed SST and CPUE of chum salmon in June and July. Yellow and orange colors of more than 10°C of observed SST moved northward gradually, as the year passed. The contour line of CPUE of 10 also moved northward. These indicate that the distribution of chum salmon shows a northward movement with warming of sea water.

The area of chum salmon distribution which was estimated using gSST is shown in Fig. 3(a), (b). In summer, the area of chum salmon distribution extended north of 40°N in the North Pacific except for the United States west coast area. The southern limit of chum salmon distribution in August and September is located to the north in comparison with that in July (Fig. 3(a), (b)). Thus, the area of chum salmon distribution in July was more extensive than that in August and September. The area of August was approximately the same area as September. The averaged area of chum salmon distribution in the 21st century was smaller than that in the 20th century (Fig. 3(c)). Ratio of the averaged area of salmon distribution in the 21st century to that in the 20th century was about 95%. The southern limit of chum salmon distribution in the 21st century moved approximately 2° northward in the North Pacific except for the United States west
coast area in comparison with the 20th century (Fig. 3(c)). This decreasing area corresponded to the Transition Domain. In July and August, decreasing area in the eastern North Pacific was larger than that in the western North Pacific in the 21st century. In September, decreasing area in the western North Pacific was relatively large. An averaged gSST in the 21st century minus an averaged gSST in the 20th century was positive in the whole North Pacific except for the United States west coast (Fig. 3(d)). This result means that SST in the 21st century in the North Pacific in summer was warmer than that in the 20th century.

The horizontal distributions of long term trend of gSST in summer showed a positive trend in the North Pacific except for the United States west coast (Fig. 4). Area of a statistically significant positive trend was spread at 42°N zonally in July and August (Fig. 4(a), (b)). In August, the trend in the Bering Sea was also statistically significant (Fig. 4(b)). In September, area of a statistically significant positive trend appeared in western North Pacific (Fig. 4(c)). The maximum increasing trend was about 0.07°C/year. The interannual change in gSST at the grid near the coast of Hokkaido had a positive trend in summer. The decreasing area of chum salmon distribution corresponded to the area of relatively large positive trend of gSST in the North Pacific. These results indicate that SST in the whole North Pacific except for the United States west coast area was warming and in particular, the warming in SST in the southern limit of chum salmon distribution was remarkable.

The mean area of chum salmon distribution in July was wider than that in August and September as previous mention (Fig. 5). The interannual change of the area of chum salmon distribution was smaller than the seasonal change. However, the interannual change in the area of chum salmon distribution in the North Pacific in summer had a statistically significant negative trend (P<0.01). The decreasing trends of the area of chum salmon distribution were -40413 km²/year in July (Fig. 5(a)), -35857 km²/year in August (Fig. 5(b)) and -30851 km²/year in September (Fig. 5(c)), respectively. It is noteworthy that the area of salmon distribution in the North Pacific in summer has decreased approximately 10% during 35 years.

Since in this study, the distribution area of the chum salmon was estimated from 30°N to 65°N, the lower thermal limit was not detected in the North Pacific and the Bering Sea in summer. It is suggested that the lower thermal limit is located in the Arctic Ocean. Even if the distribution area in the North Pacific and the Bering Sea decrease, the distribution of chum salmon may extend to the Arctic Ocean in summer. Thus, the decrease of the distribution area which was calculated using gSST may be overestimation. Upper thermal limit was located in northern offshore area of Japan in August and September. Japanese chum salmon have to approach to their natal river passing through areas where water temperature is higher than the upper thermal limit. From the results of archival tag data, chum salmon did not always stay at the sea surface in the offshore area, and the near coastal areas of Japan, chum salmon dive into deeper water to avoid warm water (Ueno, 1992; Wada and Ueno, 1999; Tanaka et al., 2000; Azumaya and Ishida, 2005; Azumaya et al., 2016). Thus chum salmon seem to have the behavioral flexibility to be able to adapt to ocean environment conditions.

Significant negative correlations between interannual change in the area of distribution of chum salmon and that of SST from 40°N to 50°N in the North Pacific (Fig. 6(a), (b), (c)) were found. There is also a negative significant correlation near the coast of Hokkaido. This means that when SST near the coast of Hokkaido rises, the area of chum salmon distribution decreases in the North Pacific. Thus, if the SST near the coast of Hokkaido is monitored, the variation in the area of the distribution of chum salmon in the North Pacific can be estimated.

It is found that the global warming of sea surface in the North Pacific in summer is progressing and the area of chum salmon distribution is decreasing. It is necessary to continue to monitor the variation in SST in the North Pacific.
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REFERENCES


Fig. 1. (a) Location of Kushiro Hokkaido, Japan and schematic view of the two fronts. (b) Interannual change in the anomaly from mean sea surface temperature at Kushiro Hokkaido, Japan from 1980 to 2017. Red indicates a positive anomaly and blue a negative anomaly. Thin line indicates long term trend which is 0.045°C/year.

Fig. 2. Time and space structure of interannual variation of the observed SST (color) by the research vessels and CPUE of chum salmon (red and black contour lines) from 30°N to 65°N. X-axis is year and Y-axis is latitude. Yellow and orange colors are more than 10°C. Red thick contour line is 10. Black thick contour lines interval is 50.
**Fig. 3.** Horizontal distributions of the area of chum salmon distribution and SST. Lines is contour lines of SST and green shows the area of chum salmon distribution in the 20th century (a) and in the 21st century (b). Thin contour interval is 1°C and thick contour interval is 5°C. (c) The difference between the area of chum salmon distribution in the 20th century and the 21st century. Red shows that the southern limit of chum salmon distribution has shifted northward during the 20th to the 21st century. Black shows that the southern limit shift southward. (d) The horizontal distribution of the difference between SST in the 21st century and that in the 20th century. The contour interval is 1°C. Yellow and orange colors indicate that SST in the 21st century is higher than that in the 20th century. A blue color indicates SST in the 21st century is lower than that in the 20th century.
Fig. 4. Horizontal distributions of the trends of SST in summer. (a) July, (b) August, (c) September. Thick black contour line indicates 0.05°C/year. Yellow and orange colors are positive trend. A blue color is negative trend. The area enclosed by the thick white contour lines indicates a statistically significant (P<0.05) positive trend. The red indicate the area that the southern limit of chum salmon distribution shifts northward during the 20th century to the 21st century.

Fig. 5. Interannual change in the area of chum salmon distribution in the North Pacific in summer (red lines). (a) July, (b) August, (c) September. Horizontal thin line indicates mean from 1982 to 2016. Sloped thin line indicates the trend in each of the three months. Broken lines indicate the standard deviation.

Fig. 6. Horizontal distributions of the correlation coefficient between the interannual change in the area of chum salmon distribution and the interannual change in SST. (a) July, (b) August, (c) September. Thin contour line interval is 0.1. Thick contour line interval is 0.5. Pink color is positive correlation and blue color is negative correlation. The red indicates the area that the southern limit of chum salmon distribution shifts northward during the 20th century to the 21st century.