First NPAFC-IYS Workshop on
Pacific Salmon Production in a Changing Climate

Technical Editors: Jeongseok Park and Stephanie Taylor

Vancouver, Canada, 2018
First NPAFC-IYS Workshop on *Pacific Salmon Production in a Changing Climate*

*Khabarovsk, Russia, May 26–27, 2018*

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Preface

The International Year of the Salmon (IYS) is an international framework for collaborative outreach and research, and seeks to increase understanding and raise awareness of the challenges facing salmon and the measures to support their conservation and restoration against increasing environmental variability. The overarching theme of the IYS is “Salmon and People in a Changing World”, and the proposed research themes are (1) status of salmon; (2) salmon in a changing salmosphere (the current and future geographic range of salmon); (3) new frontiers; (4) human dimension; and (5) information systems. These five research themes are integrated into the current NPAFC Science Plan (2016–2020), whose goal is to understand variations in Pacific salmon production in a changing climate (https://npafc.org/science-plan/). The North Pacific Anadromous Fish Commission (NPAFC) hosted the First NPAFC-IYS Workshop on “Pacific Salmon Production in a Changing Climate” on May 26–27, 2018 at the Boutique Hotel, Khabarovsk, Russia.

The workshop was attended by over 60 international salmon experts and scientists. Workshop participants presented 26 oral presentations and eight posters addressing the following topics related to the IYS research themes:

- Status of Pacific salmon and steelhead trout
- Pacific salmon and steelhead trout in a changing North Pacific Ocean
- New technologies
- Management systems
- Integrated information systems

At the workshop participants shared and reviewed knowledge of the distribution, growth and survival of Pacific salmon in the ocean; review the causes of variations in Pacific salmon production; anticipate future changes in the production of Pacific salmon and the marine ecosystems producing them; and identify research priorities and international cooperative research plans for the IYS initiative.

The Workshop Organizing Committee consisted of Alexander Bugaev (Co-Chairperson; Kamchatka Fishery and Oceanography Research Institute, Russia), Ed Farley, Jr. (Auke Bay Laboratories, Ted Stevens Marine Research Institute, NMFS, USA), Jim Irvine (Pacific Biological Station, DFO, Canada), Ju Kyoung Kim (Inland Life Resources Center, FIRA, Korea), Denis Kotsyuk (Khabarovsk Department, TINRO-Center, Russia), Svetlana Naydenko (Pacific Scientific Research Fisheries Center, TINRO-Center, Russia), Mark Saunders (International Year of the Salmon (IYS) North Pacific Steering Committee, Canada), Shigehiko Urawa (Co-Chairperson; Hokkaido National Fisheries Research Institute, FRA, Japan), and Jeongseok Park (NPAFC Secretariat).

The following workshop topic chairs led discussion during the workshop: Jim Irvine, Nataliya Klovach, Alexander Bugaev, Ed Farley, Jr., Suam Kim, Svetlana Naydenko, and Mark Saunders.

On behalf of the Workshop Organizing Committee, we thank all presenters and participants for sharing information and addressing the topics related to the IYS research themes at the workshop and for submitting materials for this volume.

Technical Report No.11 is a compilation of extended abstracts submitted by workshop presenters, and it concludes with a wrap-up summary and research priorities identified at the workshop. Material in this report has not been peer-reviewed and does not necessarily reflect the views of NPAFC, member countries, or authors’ agencies. I thank Stephanie Taylor (2018 NPAFC Intern) for the help of editing the extended abstracts. Abstracts have been edited for clarity and publication purposes.

Jeongseok Park
Deputy Director, NPAFC
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Status Overview for Pacific Salmon Populations in the Eastern North Pacific Ocean

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Keywords: Pacific salmon, stock status, Eastern North Pacific, abundance, North American salmon

Pacific Salmon in the eastern North Pacific (Fig. 1), dominated by Chum, Pink, and Sockeye Salmon, are at relatively high levels in terms of numbers and biomass, although there is evidence of recent declines (Fig. 2, Ruggerone and Irvine 2018). To assess the status of salmon in this region we assembled information gathered by American and Canadian researchers. In the US, salmon are primarily managed to provide sustained yield; spawner escapement goals are set for stocks, or aggregates of stocks, for each species within geographic areas. The proportion of stocks within an area that achieve these goals provides an indication of status for that return year. In Canada, salmon are primarily assessed as individual or aggregates of Conservation Units (CUs), which are genetically or ecologically distinct groups of salmon. CU-specific biological benchmarks, based primarily on salmon abundance and distribution delimit three biological status zones: green (healthy status), amber (intermediate) and red (poor). Here we describe the biological status of each of the five major species in the US and Canada, provide information on changes in fish size and age composition if noteworthy, and comment on possible reasons for recent changes.

Chinook Salmon are generally doing poorly throughout the eastern North Pacific, suggesting that large-scale environmental processes are primarily responsible for their current status. In Alaska, Chinook Salmon have experienced downturns in abundance over the past two decades. Despite some recent improvements in meeting escapement goals in central and western Alaska, abundances since 2007 have been some of the lowest on record throughout Alaska (Fig. 3, Munro in press). Chinook in the Canadian portion of the Yukon River are also below long-term average levels, and many CUs in southern British Columbia (BC) are in the red zone (Fig. 4, DFO 2016a). In Puget Sound and the Columbia River, wild salmon returns have declined and runs are dominated by hatchery-origin Chinook Salmon (Fig. 5, Dufault et al. 2018). There has been a shift to younger age classes returning throughout their range with some populations showing decreases in size at age (Ohlberger et al. 2018).
Fig. 3. Annual percentages of Alaska Chinook Salmon stocks achieving escapement goals (adapted from Munro in press) and corresponding commercial harvests (adapted from Brenner et al. 2018).

Fig. 4. Map of southern BC summarizing workshop consensus on biological status of southern BC Chinook Salmon CUs. From DFO (2016a).

Sockeye Salmon status is highly variable with populations in the Bering Sea and northern Alaska Current generally doing better than populations in southern BC, implying a potential temperature effect. Interestingly, Sockeye from the Columbia/Okanagan and West Coast of Vancouver Island that enter a different marine ecosystem appear to be responding somewhat differently than more northerly populations, sometimes doing better. Marine growth during odd-numbered years for many Sockeye from Alaskan and some BC populations is reduced compared with growth in even-numbered years, potentially in response to higher numbers of Pink Salmon in odd-numbered years (Ruggerone et al. 2015; 2016). In Alaska, most stocks are in average to good condition with recent increases in commercial harvest and high proportions of escapement goals being met (Fig. 6; Munro in press, Brenner et al.)
High numbers can be associated with reduced growth; recent weights of Bristol Bay and Copper River Sockeye have been well below long-term averages (Fig. 7; ADF&G, unpublished data). In BC, large returns have generally been associated with La Niña (cool) conditions while poor returns have been linked to El Niño (warm) events. Warm marine and freshwater conditions during 2014–2017 reduced survivals for many populations, particularly for Sockeye returning in 2017. More research is required to fully understand linkages between survival and the frequency and magnitude of ENSO events (Fig. 8, Hyatt et al. 2017).

Fig. 5. Numbers of hatchery and wild-origin Chinook Salmon returning to Puget Sound, Washington State (Dufault et al. 2018).

Fig. 6. Annual percentages of Alaska Sockeye Salmon stocks achieving escapement goals (adapted from Munro in press) and corresponding commercial harvests (adapted from Brenner et al. 2018).

Fig. 7. Average annual weights of Copper River Sockeye Salmon caught in commercial fisheries (S. Haught, ADF&G, unpublished data).
Fig. 8. Trends in the total returns (black line) and resource manager forecasts (blue dashed line) for BC Sockeye Salmon index stocks including: (1) Stikine—Tahltan; (2) Nass—Meziadin; (3) Smith Inlet—Long; (4) Fraser—Chilko; (5) Barkley Sound—Somass; and (6) Columbia—Okanagan. Y-axis represents returns in thousands of fish. From Hyatt et al. (2017).

Fig. 9. Annual percentages of Alaska Coho Salmon stocks achieving escapement goals (adapted from Munro in press) and corresponding commercial harvests (adapted from Brenner et al. 2018).

Coho are perhaps the most difficult salmon species to assess since they return late in the season and do not aggregate in large groups. In most of Alaska, escapement goals have usually been achieved in recent years (Fig. 9; Munro in press). However, Coho have been returning at smaller sizes for the past 3 decades, and, similar to Sockeye Salmon, Coho often return at smaller sizes in odd-numbered than even years (Fig. 10; L. Shaul, unpublished).
In BC, Coho Salmon are generally doing less well in southern regions than northern regions and those from the interior Fraser River watershed are doing the poorest (e.g., DFO 2016b, DFO 2018). Survivals of hatchery and naturally produced Coho Salmon smolts entering the Salish Sea (Canada’s Strait of Georgia and US Puget Sound) have declined over the past 3 decades, in contrast to other Coho Salmon that enter outside waters, suggesting that changing conditions early in the marine lives of Salish Sea Coho may be particularly important in determining brood stock strength (Fig. 11, Zimmerman et al. 2015).

**Fig. 11.** Coho Salmon smolt survival time series for ocean entry years 1977 to 2010 for (A) the Strait of Georgia, (B) Puget Sound, and (C) the Pacific coast. The thin lines represent individual populations: the thin gray lines are hatchery populations and the thin blue lines are wild populations. The thick lines show the predicted survival for hatchery (black) and wild (blue) populations in each region. From Zimmerman et al. (2015).

Status and returns of Pink Salmon often differs between genetically distinct even- and odd-year brood lines. In Alaska, most odd-year returning Pink Salmon have been meeting or exceeding escapement goals while providing large harvests. There has, however, been a decline in the proportion of escapement goals met for even-year returning Pink Salmon, which has also coincided with low harvests (Fig. 12, Munro in press, Brenner et al. 2018). In BC, returns of odd-year brood line have tended to be stable or increasing while even-year fish populations are stable or declining (Fig. 13, Irvine et al. 2014).

**Fig. 12.** Annual percentages of Alaska Pink Salmon stocks achieving escapement goals (adapted from Munro in press) and corresponding commercial harvests (adapted from Brenner et al. 2018).
Chum Salmon are generally doing well throughout their range. In Alaska, the majority of stocks currently achieve their escapement goals (Munro in press) and commercial harvests remain high (Fig. 14; Brenner et al. 2018). Chum Salmon tend to be doing less well in northern BC than in the south, although there are exceptions. There is some evidence of an interaction between density and climate effects on marine growth for Chum Salmon in southern BC (Debertin et al. 2017). Numbers of Chum Salmon in Puget Sound, Washington State remain high (Fig. 15, Dufault et al. 2018).

Fig. 13. Status of (A) even-year and (B) odd-year Conservation Units (CUs) of Pink Salmon depicted by five-piece circles in which the central number is the number of the CU and each piece shows the results from one time series approach. The colors represent different status zones. Each circle is placed in the area of the freshwater distribution of that CU. From Irvine et al. (2014).

Fig. 14. Annual percentages of Alaska Chum Salmon stocks achieving escapement goals (adapted from Munro in press) and corresponding commercial harvests (adapted from Brenner et al. 2018).

Fig. 15. Numbers of Chum Salmon returning to streams in Puget Sound, Willapa Bay, and Grays Harbor, Washington State (Dufault et al. 2018).
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Current Status of Chum and Pink Salmon: What is Reducing Adult Returns in Japan?

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Keywords: juvenile salmon, early marine survival, sea surface temperature, brood strength, Amur chum, anomalous ocean conditions

In Japan, the annual catch of chum salmon (Oncorhynchus keta) has decreased remarkably since 2010, and by 2016 and 2017 the catches of adults had returned to the low levels seen in the early 1980s, when the annual number of released chum fry was approximately the same as the present level of 1.8–2 billion. The decline in catches is especially evident in the region of the southern part of the Okhotsk coast to the Pacific coasts of Hokkaido and Honshu islands. By comparison, pink salmon (O. gorbuscha) are mainly captured along the Okhotsk coast of Hokkaido. Catches of pink salmon have declined sharply since 2011; except for improved returns in 2016, and recent catch levels are comparable to those in the early 1980s and pre-1980s. Thus, the main purpose of this study was to clarify the reasons for the recent declines in adult salmon catches in Japan.

Massive mortalities of salmon often occur during the early life stages in the marine environment, and juvenile salmon survival often affects the brood-year strength or overall adult returns (Pearcy 1992; Beamish and Mahnken 2001). To examine the effects of the coastal environment during the early life history on the brood-year strength of chum salmon, we conducted correlation analyses between data on coastal sea surface temperatures (SSTs) and brood-year strength among the brood years 1989–2013 in four regionally aggregated chum stocks (i.e., Nemuro region, NE; East Erimo Peninsula region, EP; West Erimo Peninsula region, WP; and Honshu Pacific region, HP), wherein poor adult returns were recognized in recent years. In this analysis, the numbers of returning adult chum salmon (i.e., the coastal catch + in-river catch) up to age 0.3 were indexed as denoting the brood-year strength for each region. The original SST data were 10-day mean SSTs analyzed for 0.25-degree mesh grids, as provided by the Japan Meteorological Agency (NEAR-GOOS RRTB: http://ds.data.jma.go.jp/gmd/goos/data/database.html). SST data was selected for the period from early March to late July for the years 1990–2014, for the following areas: Area I: 43.25ºN–46.25ºN, 142.00ºE–146.25ºE for the NE chum; Area II: 41.00ºN–43.25ºN, 143.25ºE–146.25ºE for the EP chum; Area III: 41.00ºN–42.50ºN, 142.25ºE–143.25ºE for the WP chum; and Area IV: 35.75ºN–41.00ºN, 142.50ºE–143.25ºE for the HP chum. Since many correlation analyses were conducted over each of the four areas (at 10-day intervals during early March to late July), we summarized the results as the percentages of mesh grids showing statistically significant positive (negative) correlation to the total number of mesh grids in which the correlation analyses were conducted.

The correlation analyses revealed that statistically significant positive correlations were dominant mainly for March to May for all the areas, meaning that the brood-year strength of each regional chum stock positively correlated with SSTs within each corresponding area. Since the period when the positive correlations were dominant corresponded to the time when juvenile chum salmon start their marine life, conditions of warmer SSTs tended to be associated with better survival of the chum broods from these four regions. However, SST anomalies in March to May tended to be frequently negative after the 2000s in Areas II, III and IV. Although such lower SST anomalies were not evident in Area I, the SSTs in late May—when the positive correlations were the most dominant in the correlation analyses—showed frequent negative anomalies after the 2000s, suggesting that the NE chum had been regularly exposed to lower SSTs during their early marine life. Furthermore, since 2010, an abrupt change from a negative SST anomaly during March to May, to a positive SST anomaly during June to July was frequently observed. Such an abrupt change in the SST anomaly was evident in 2013 and 2014, which likely determined the poor returns of adult chum salmon in 2016 and 2017. Abrupt changes in the SSTs from negative to positive anomalies were also observed for the coastal waters along the Okhotsk coast of Hokkaido during the spring and summer of 2010 and onward; a situation likely linked to the poor returns of adult Japanese pink salmon in recent years (Saito et al. 2016).

A statistically significant correlation was found between the chum salmon catch in Japan and that in Russia during 2003 and 2016 ($r = −0.81, p < 0.0001$), based on NPAFC statistics. To understand the opposite trends in
chum catches between Japan and Russia, we analyzed a Beverton–Holt (BH) model for Amur River chum, using catch data for 1989–2016. Since the Amur River chum stocks are mainly sustained by wild salmon, variability in the catch is probably affected by the extent of natural spawning (i.e., escapements). To estimate escapements for 1989–2012, we assumed an exploitation rate of the stock set at 0.39, which was calculated as a trimmed mean value from estimations of Russian escapements and the catch data for 1993–2013, but excluding the years of 2003 and 2008. The relationship between numbers of escapements in year $t$ and the numbers in the catch plus escapements in year $t + 4$ ($t = 1989–2012$) revealed that greater adult catches of Amur chum occurred after 2005 ($t = 2005$). The residuals of the BH model were positively correlated with the 0.25-degree-mesh gridded SSTs, during early May to late July for the period 1990–2013, for a wide range of ocean areas in the vicinity of the Amur River mouth ($53^\circ$N–$55^\circ$N, $140^\circ$E–$142^\circ$E); this result suggests that warmer SSTs were associated with better survival of the Amur River chum stock. In particular, a higher correlation coefficient was observed between the residuals and averaged SST anomalies in mid-June for the ocean areas ($r = 0.75$, $p < 0.001$), and the 2005–2012 broods that showed greater adult returns in recent years had experienced warmer SSTs during the juvenile life stage. Accordingly, the recent higher returns of Amur chum were possibly supported by warmer ocean conditions during their early marine life.

Warmer SSTs during their period of coastal residency are probably associated with better survival of Japanese chum originating from the southern part of the Okhotsk coast and the Pacific coast of Japan, as well as Japanese pink and Amur chum salmon. However, SSTs in the Pacific coastal waters off Japan tended to be lower since the 2000s, with an abrupt shift from low to high anomalies of SSTs often evident since the 2010s. Unlike Japanese coastal waters, SSTs in the Sea of Okhotsk near the Amur River mouth became warmer after the mid-2000s. Such an opposite trend in the SSTs during the early marine life of the salmon probably generated a difference in the productivity of salmon between Japan and Russia in recent years. Elucidating the mechanisms responsible for the opposite trends in the chum catches between Japan and Russia may assist us with understanding regional shifts in salmon production as a consequence of climate change.

REFERENCES


Return of Chum Salmon with Latitude and Marine Environment in the Eastern Coast of Korea

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Keywords: climate change, fisheries, returning

Chum salmon, *Oncorhynchus keta*, has the largest natural distribution range among salmon species inhabiting the North Pacific regions. River spawning sites of chum salmon in the Northwest Pacific are found throughout Russian, Japanese, and Korean rivers. The western coast of the East/Japan Sea (WEJS) is the southern limit of chum salmon distribution. However, the specific migration route of chum salmon in the WEJS from sea to river or vice versa is still unclear. This basic ecological knowledge including migration routes and distribution patterns is essential for effective management of salmon resources. In this study, we investigated whether arrival timing and movement patterns of chum salmon have been influenced by oceanic conditions around Korea waters. Results from our studies may be helpful in enhancing ecological knowledge and improving management of chum salmon and possibly connected to climate change.

In the WEJS, horizontal distributions of water temperature in October, when the majority of chum salmon travel up rivers for spawning, are summarized as two types of periods (i.e., cold and warm oceanic conditions) (Fig. 1). During the warm period, water temperatures along the coast of the WEJS were higher than normal, while the water temperatures in this area were colder than normal during the cold period (Fig. 1). Such an alteration of cold and warm patterns was closely dependent on the strength of Tsushima Warm Current (TWC). In particular, strong volume transport of the TWC via the Korea Strait (KS) has pushed the main path of East Korea Warm Current (EKWC, branch of the TWC in the WEJS) northward along the eastern Korean coast resulting in changes to the water temperature structure in the WEJS (Fig 2). These oceanographic modifications in the WEJS probably control arrival timing and movement pattern of adult chum salmon.

The set net fishery landing data show that there were some latitudinal differences in chum salmon arrival timing (Fig. 3). Adult salmon return to their natal rivers between September and December; however, the horizontal distribution pattern of adult salmon arrivals was different by latitude. In the R-4 site (around 38°N), the adult salmon first appeared in early September, whereas arrival timing in the other regions has been later than in the R-4 region (Fig. 3). The results indicated that adult chum salmon first arrived at the R-4 site, and in turn moved north and/or southward to their natal rivers. Because the coastal area around R-4 region also is known as the eastern tip of the subpolar front in EJS, adult chum salmon have been expected to use the subpolar front as one of the river migration routes. In addition, there also were somewhat south-northern variations in the catch of coastally arrived adult chum salmon according to the path of the EKWC and the extent of TWC volume transport via the KS in the...
WEJS (Fig. 4; see also Fig. 1). During the warm period, the catch ratio of adult chum salmon tended to be higher in the northern areas (R-1 and R-2 sites), while the opposite trend was evident during the cold periods (Fig. 4).

**Fig. 3.** Horizontal distribution of arrival timing of adult chum salmon during warm and cold periods. Left panel = warm period, middle panel = cold period, right panel = station maps from R-1 to R-11.

**Fig. 4.** Catch ratio of chum salmon between warm and cold period in each of the 11 regions on the eastern coast of Korea.

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Current Stock Assessment of Pacific Salmon in the Far East of Russia

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Keywords: Pacific salmon in Far East of Russia, catch, trends in the dynamics of catches

All six species of the genus Oncorhynchus spp. are reproduced in the Russia Far East. The huge length of the reproductive area of Pacific salmon in the Russian Far East, different climatic conditions of reproduction and feeding, and various terms of spawning migration determine the different dynamics of stocks in the regions, both in general, and in particular salmon species.

As of 2017, Russian salmon stocks remain in general at a high level, but slightly below the level of recent years. The total catch of all Pacific salmon species by the coastal fishery in the Far East in 2017 was 353,000 metric tons, which is 13,000 metric tons less than the catch of 2015 and 85,000 metric tons less than the catch in 2016 (Fig. 1). Out of these 353,000 metric tons, 241,000 metric tons were caught in Kamchatka with 163,000 metric tons caught in its northeastern part. In all other regions, 112,000 metric tons of salmon were caught in total. The salmon approaches to the Northeast Kamchatka in 2017 were the third largest and the catch was the second largest in the history of the fishery in this region (Shevlyakov et al. 2017).

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All six species of the genus Oncorhynchus spp. are reproduced in the Russia Far East. The huge length of the reproductive area of Pacific salmon in the Russian Far East, different climatic conditions of reproduction and feeding, and various terms of spawning migration determine the different dynamics of stocks in the regions, both in general, and in particular salmon species.

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In recent years due to the warming of the ocean, the main areas of salmon reproduction shifted to the north. As the result, salmon abundance and catch increased in the northern regions (Kamchatka and Continental Coast of Okhotsk); while importance of southern reproduction areas (Sakhalin and South Kuril Islands) decreased (Fig. 2a).

**Pink salmon Oncorhynchus gorbuscha**

Pink salmon constitute about 55–75% of the total salmon catch in the Far East. Therefore, it is the trends in the dynamics of their stocks that determine trends in the dynamics of all salmon stocks in Far East (Fig. 2b). Rise of Kamchatka pink salmon stocks in 2015–2017 was associated with a very sharp warming of water in the Northeast Pacific in 2014–2016 and the subsequent advection of heat into the Bering and Okhotsk Seas observed in all seasons of the year (Krovnin et al. 2016). The pink salmon catches in the East and West Kamchatka are strongly correlated, when East Kamchatka catch increases, it leads to increases in West Kamchatka catch the next year (Fig. 3a). However, decline of the Sakhalin Coast stocks continued in 2015–2017 under the influence of both adverse environmental conditions at early life stages and poaching in the rivers (Fig. 3b).

![Fig. 3. Dynamics of pink salmon catch in Western and Eastern Kamchatka (a) and Eastern Kamchatka and Sakhalin Coast (b) in 1949–2017.](image)

The intensive growth of Sakhalin pink salmon stocks was noted in the early 2000s, that resulted in the historical maximum of catches of both generative lines. This was associated mainly with an increase in survival during the marine life period. In 2015–2017 there was a sharp reduction in the number of pink salmon. After 2012 the tendency towards a decrease in sea surface temperature (SST) in the southern Okhotsk Sea has appeared. Apparently, it resulted in a decline in Sakhalin salmon stocks. In addition, in the southern Okhotsk Sea in winter-spring seasons of 2014–2017 there was an increased intensity of cyclonic activity and frequent occurrence of typhoons with heavy rainfall. These factors also contribute to decreases in pink salmon stocks in the eastern Sakhalin and South Kurils. At the same time, in the South Kurils, in contrast to the Sakhalin Coast, declines in pink salmon catches in 2011–2015 were replaced by their rise in 2016 and 2017. It should be noted that both in Sakhalin and in the southern Kuril Islands, the basis of returns was the late temporal form of pink salmon in recent years (Kaev 2012; Kaev and Sidorenko 2015; Klovach et al. 2017; Romasenko et al. 2017).

![Fig. 4. Catch Dynamic of Amur basin Pink Salmon in 1900–2017.](image)
At present, even-year generations of Amur and Primor’e pink salmon stocks and their catches exceed the level of the early 20th century (Ostrovsky 2014). One of possible reasons may be associated with effects of continental hydrometeorological processes in winter on survival during embryonic development in nests (Fig. 4).

**Chum salmon Oncorhynchus keta**
Chum salmon stocks are currently at high levels. From 2001 to 2015, their catches in the Far East have increased more than five times, from 28,000 to 142,000 metric tons (Volobuev et al. 2017). Since 2016, decline in catch of chum salmon has been noted. In 2017, catch of chum was 98,000 metric tons in all regions of the Far East (Fig. 5a). The contribution of chum salmon catches from different regions to the total salmon catch in the Far East varied with time. In recent years, the largest contribution of chum salmon to total catches was from the Amur basin stock (Fig. 5b). Its catches from 2001 to 2015 increased 17 times, from 2,140 to 36,700 metric tons. In 2017, Amur chum salmon catch was 26,100 metric tons. Decrease in the catch of the Amur chum in 2017 is generally due to the decrease in the catch of the summer race (Fig. 6).

**Fig. 5.** Chum salmon catches in the Russian Far East in total (a), and in various regions (b) in 2001–2017.

**Fig. 6.** Dynamic of Amur summer and fall chum salmon catch in 1950–2017.

**Sockeye salmon Oncorhynchus nerka**
Sockeye salmon stocks—the third numerous species of Pacific salmon in the Russian Far East—are at high levels. Their catch of 42,100 metric tons in 2017 was slightly lower compared to previous two years. This catch consists mainly of fish from two stocks—stock of Kurilskoe Lake in the West Kamchatka and stock of the Kamchatka river in the East Kamchatka. The abundance of both stocks are now at high levels in Kamchatka. In
2017, 40,000 metric tons of sockeye salmon were caught in Kamchatka waters. In other areas, such as Chukotka, Continental Coast of Okhotsk and Kuril Islands, 2,100 tons in total were caught.

*Coho salmon Oncorhynchus kisutch*

Coho salmon catch in 2017 was about 7,000 metric tons. This is less than half of the catch in 2015 and 2014 (14,500 metric tons). About the same amount was caught in 2016. Nevertheless, now Kamchatka coho salmon stocks are above mean long-term level. There is also an increase in Continental Coast coho salmon stocks (645 metric tons).

*Chinook salmon Oncorhynchus tshawytscha*

The catch of Far East Chinook in 2017 was 388 metric tons, which was more than two times lower than in 2016 (818 metric tons). The abundance of the East Kamchatka stocks has stabilized at an average level. However, the catch-by-weight is lower than in the 1990s due to a decrease in the proportion of females, their rejuvenation, and reduction in body weight (Shevlyakov et al. 2017). The population of the Bolshaya River Chinook salmon (West Kamchatka) is in a depressed state now (Fig. 7). Commercial fishing of cherry salmon has been closed for many years, however, catching cherry salmon for fish farming, scientific research purposes, and sport fishing still occurs.

![Fig. 7. Chinook salmon in Kamchatka river (East Kamchatka) in 1958–2017.](image)

*The contribution of artificial reproduction of Pacific salmon to stocks and catches*

There are 68 salmon hatcheries in the Far East. In 2017, they released 1,043,500 juveniles in total; 82.6% of juveniles were released from the Sakhalin and Iturup hatcheries. Chum and pink salmon constituted 99.2% of the hatchery fish released (Fig. 8). The growth of catches of chum salmon in Sakhalin and the southern Kuril Islands from 3,598 metric tons (on average for 1991–2000) to 33,573 metric tons (on average for 2011–2015) was mainly due to the development of artificial reproduction. Changes in chum salmon hatchery culture since the 1990s—reconstruction of the operating hatcheries, progress in biotechnology, appearance of new hatcheries with a private property form—have led to a substantial growth of their catches. In the recent years a method of the out-of-hatchery culturing of chum juveniles began to be approbated. Currently, up to 90% of Sakhalin and Iturup chum salmon are represented by hatchery fish. The problem of the effectiveness of pink salmon culture relative to the increase in their commercial catches is shown to remain controversial (Morita et al. 2006; Kaev and Ignatyev 2015; Klovach et al. 2017).
Fig. 8. Share of salmon fry and smolts hatchery releases by area (a) and species (b) from the total production in the Far East in 2017, %.

Summary

The anomalous surface warming started in autumn 2013 which had spread into the western Bering Sea by spring 2014, and in 2015/2016 it reached the North Kuril area and northern Okhotsk Sea. This was accompanied by northward shift of reproduction areas of pink salmon. As a result of increased marine survival of the northern pink salmon stocks (West and East Kamchatka and Continental Coast of Okhotsk), their approaches to the coast and catches increased. At the same time, the Sakhalin and South Kuril pink salmon stocks decreased. In 2017, all chum salmon stocks were at a high level but somewhat lower than during two previous years. All chum salmon stocks except for the South Kuril and Sakhalin stocks, were maintained by means of natural reproduction. The South Kuril and Sakhalin stocks were maintained by artificial reproduction, approximately 90% of the stocks are hatchery fish. Coho and sockeye stocks, originated mainly from Kamchatka, are in a good state now. Further research is needed to explain the reasons of sharp increase in Amur and Primor’e pink salmon stocks in even years, as well as the reasons of degradation and changes in biological features of Kamchatka Chinook salmon.

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Activity of Extreme Environmental Factors as a Reason for Pink Salmon Abundance Decline in the Sakhalin-Kuril Region, Russia

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Keywords: Sakhalin Island, Iturup Island, pink salmon, abundance, extreme factors (floods, storms in sea coasts)

Some changes in pink salmon abundance from 2007–2017 have been studied on Iturup Island and four areas of the eastern Sakhalin coast. An abrupt decline in abundance was observed in broodlines which appeared to be due to the influence of extreme environmental factors. The extreme events were both the floods caused by abnormal high precipitation that destroyed spawning grounds, and the storms on the seacoast during the mass fry downstream migrations to the sea. Estimated run sizes of pink salmon in 2017 in the monitored areas fully agreed with the ascertained dependences for the preceding period. These results show a decisive role of extreme environmental factors in pink salmon abundance formation.


Fig. 2. Dynamics of pink salmon catch in certain areas of the Sakhalin-Kuril region from 1970–2017: NES–northeastern Sakhalin, TB–Terpeniya Bay, SES–southeastern Sakhalin, AB–Aniva Bay, It–Iturup Island.

The Sakhalin-Kuril region possesses about half of the Russian catches of pink salmon, so prospective changes in its abundance are a subject of the high interest. About 90% of pink salmon are captured in the four areas of eastern Sakhalin and Iturup Island (Fig. 1). Beginning from 1970, the average annual catch was 18,981 metric tons on Iturup Island, 10,090 metric tons in Aniva Bay, 19,123 metric tons in southeastern Sakhalin, 10,112 metric tons in Terpeniya Bay, and 6,686 metric tons in northeastern Sakhalin. Also, since 1970, this catch trend has changed substantially in different years and areas (Fig. 2).

A significant decline in catches in the even-numbered years had been observed everywhere in the 1980s, while in the mid of that 10-year period the catches increased in the odd-numbered years. After a short-term decline in 1993, catches in eastern Sakhalin tended to increase in odd-numbered years, and increase on Iturup Island in even-numbered years where the dominants had changed. In the last 10 years, both pink salmon broodlines have reached
historical maximum of catches. At the same time, increases and/or decreases in catch rates differed by areas, and their peaks and falls were not strictly synchronous in the different areas. Such a mismatch is noticeable for the last 10-year period. The maximum catches were prematurely taken in southern areas, and the decrease in catches for dominant broodlines started ahead of time in the same areas (Iturup Island and Aniva Bay). In May 2015, a hypothesis about the forthcoming significant decline in catches of northern part of eastern Sakhalin (Kaev 2015) was reported at the NPAFC International Symposium on Pacific Salmon and Steelhead Production in a Changing Climate: Past, Present, and Future taking place in Kobe (Japan). Later in 2015, that event had actually happened.

There is an uncertainty surrounding the reasons for such abrupt and time-unmatched declines in pink salmon catches in neighboring areas. Previous work has shown that the mean statistic values of the environmental parameters cannot be used for predicting such changes in pink salmon abundance. The reason behind this is that fish populations have certain resistance to environment fluctuations. So, significant changes in their abundances should occur, to a greater extent, because of the casual (rare, unusual) environmental factors (Kaev 1989; Kriksunov 1995). Both the abnormal high autumn floods that destroy grounds on the spawning areas (Kaev 1983; Putivkin 1989; Kaev and Chupakhin 2003), and sea storms that strongly affect the fry recently migrated downstream (Kaev 1992) should be related to these factors for the first turn. To examine this hypothesis, we used the data of meteorological stations on numbers of precipitation and strength of winds (https://rp5.ru, the data are at the disposal since 2005), which were correlated with the abundance of pink salmon of the corresponding broodlines.

The probability of the rain floods in rivers was determined based on the maximum sum of precipitation during the two days adjacent to the precipitation event. Since the precipitations’ falling is uneven over the vast territory, to characterize their numbers on each of the reproduction areas for pink salmon stocks studied, we tried to use the data of several meteorological stations (Fig. 1). Thus, for the Aniva Bay pink salmon, most of which spawn in rivers of western and northwestern coasts of the bay, the calculation was completed using the data obtained from stations located in Yuzhno-Sakhalinsk, Kholmsk and Nevelsk. For southeastern Sakhalin pink salmon, which spawning grounds are mainly concentrated in rivers of northern part of the area, the calculation was completed using the data of Yuzhno-Sakhalinsk and Dolinsk stations. For the Terpeniya Bay pink salmon, about half of which spawn in mountain rivers of western coast of the bay, and another part in the basin of Poronai River and adjacent rivers of the vast lowland, the calculation was completed using the data of Makarov, Pil’vo, Poronaisk, Pervomaisk, and Pogranichnoye stations. For northeastern Sakhalin pink salmon, whose percentage in commercial catches is 75% due to the fish spawning in mountain rivers of southern part, the calculation was completed using the data of Pervomaisk, Pogranichnoye, and Tyumovsk stations. On Iturup Island the calculation was completed using the data of the only station in Kitovoye, which is located in the center of the most productive spawning areas for a local pink salmon stock. We used the extreme values of precipitation exceeding 8 cm for Iturup Island, 6 cm for southeastern Sakhalin with its larger rivers, and 5 cm for the large rivers of northern Sakhalin.

A probability of the storm conditions in the sea coastal zone was determined based on the average value of the maximum wind gusts fixed during four to eight daily measurements. The data from Korsakov and Yuzhno-Sakhalinsk stations was used for Aniva Bay, the data from Yuzhno-Sakhalinsk and Starodubsk stations was used for southeastern Sakhalin, the data from Makarov and Poronaisk stations was used for Terpeniya Bay, the data from Pogranichnyi and Nogliki stations was used for northeastern Sakhalin, and the data from Kitovoye station was used for Iturup Island. In the years when observations for wind strength (2016) and amount of precipitation (2015–2016) were not carried out at Kitovoye station, the data of Yuzhno-Kurilsk station (Kunashir Island) was used for Iturup Island. The mean daily values exceeding 16 m/s were used as extreme values, except on Iturup Island where mean daily values exceeding 17 m/s were used because there are more shelters for juveniles due to the shoreline architecture of the island.

When analyzing the influence of these factors on pink salmon abundance, we should take into account the following circumstances. The proportion of hatchery-reared fish among the downstream migrating juveniles was 30–58% for the Iturup pink salmon broodlines, 17–66% for the southern part of east Sakhalin, 3–25% for Terpeniya Bay, and in northeastern Sakhalin practically all of the juveniles which migrated downstream were from spawning grounds. If in seawater, the environmental factors simultaneously affect hatchery-reared and wild fish, then in rivers the destructive action of floods will affect the products of spawning. To avoid such an imbalance, we have analyzed abundance changes only in wild fish. Fish caught were conditionally divided into wild and hatchery-reared individuals according to the ratio of numbers of fry migrated downstream from spawning areas, and those released from hatcheries; assuming they were following equal survival in seawaters. The number of fish counted in rivers on spawning grounds was added to the obtained number of wild fish captured.

Second, we took into account the timing of extreme factors, when they could cause most damage to pink salmon reproduction: floods—in the second half of the mass spawning or after its completion—and storms in the
period of mass fry downstream migration from rivers. To increase perception of timing of their actions, each year
fragment on the x-coordinate includes a conditional range of time interval between August and November (for
precipitation), and between 1 May and 10 July (for wind) (Fig. 3).

Fig. 3. Dynamics of pink salmon abundance, by odd and even broodlines (lines), number of the days with
extremely high precipitation during its spawning and soon after the spawning (columns), and number of the days
with strong wind during its juveniles feeding in the coastal sea (symbols).
Declines in abundance for pink salmon broodlines strongly affected by the extreme environmental factors were registered in all areas. The low-abundant returns of pink salmon in 2011 in Aniva Bay and the comparatively high-abundant returns in 2008 on Iturup Island are not exclusions. In the first case, the decline in abundance was caused by a strong flood in rivers flowing from the mountain ridge of western coast of Aniva Bay where the main part of pink salmon stock spawned in recent years. The flood in the second half of September was proved by the witness, fisherman K. Mitaki, and by the records of meteorological stations stated the increase in precipitation number on 18–19 September (“Nevelsk”, 3.6 cm; “Kholmsk”, 4.7 cm); the cardinal rain front could pass along the ridge from the bay side. In the second case pink salmon abundance in 2008 on Iturup Island, though comparatively high for the considered year series, decreased 1.5 times in comparison with the parent generation.

In 2015, the minimum number of adults returned to Iturup Island was caused by floods during the mass spawning process and by a storm during the period of the mass fry downstream migration. The decline in pink salmon abundance in Aniva Bay and southeastern Sakhalin in 2015 was caused by storms during the period of the mass fry downstream migration. In Terpeniya Bay and northeastern Sakhalin a decline in pink salmon abundance in 2015 was not very large because storm winds in the first area affected only the early migrated juveniles, and a flood in rivers of the second area after spawning completion was not very strong.

Based on the results of these studies we suggested that in 2017 the pink salmon abundance in southern areas of the region would remain low, and in northern areas, significant decline would be inevitable because of the record high autumn precipitation (Kaev 2018). This scenario was fully realized in eastern Sakhalin, but on Iturup Island, at first glance, the prediction was not true. Nevertheless, an unfavorable impact of extreme factors on abundance formation of this broodline took place which was proved by the dynamics of pink salmon catches in 2017. Catches in the first half of the pink salmon run were lower than the mean of preceding odd years (Fig. 4), that corresponds to both the flood passing in the middle of the spawning process of their parents, and the storms observed in the first half of the mass fry downstream migration to the seacoast. Besides, the impact of these factors on Iturup pink salmon cannot be considered very significant as the meteorological data of neighboring Kunashir Island was used to characterize spawning conditions for this broodline; due to the absence of corresponding data on Iturup Island.

![Fig. 4. Seasonal dynamics of pink salmon catch on Iturup Island in 2017 compared with the mean dynamics for preceding odd years.](Image)

The maximum values of the considered extreme environmental factors influencing pink salmon reproduction are taken as “1” for the mathematic interpretation of their total impact, and for the rest factors, parts are calculated proportionally to their values relative to these maxima. For the broodlines weakly exposed to these factors (before the mass spawning process, and before or after the mass fry downstream migration), their values are taken as “0”. Correlation of changes in pink salmon abundance with the values of extreme factors obtained on Iturup Island ($r = -0.70, p = 0.015$), in Aniva Bay ($r = -0.52, p = 0.102$), in Terpeniya Bay ($r = -0.47, p = 0.148$), in southeastern Sakhalin ($r = -0.51, p = 0.106$), and in northeastern Sakhalin ($r = -0.52, p = 0.104$) are statistically uncertain in most cases that are associated with a short series of observations (an objectivity of the occurring processes is evident). The situation is enhanced by the fact that for only four–six of 11 generations studied in each area, the values of extreme factors were variable, in the rest of the cases they were taken as “0”.
The trajectory and power of each of the cyclones are specific and produce local foci of their influence on pink salmon reproduction in the area. For example, in 2011 the decline in pink salmon abundance occurred in Aniva Bay due to the flood in rivers on its western coast, whereas the abundance of pink salmon in southeastern Sakhalin remained at a high level. In 2013, there was a decline in abundance in these both areas, but its genesis differed: a decline in abundance in Aniva Bay was caused by the impact of the autumn river flood on spawning process, and on southeastern coast it was caused by the impact of storms on the recently migrated fry. But even if the timing series of environmental factors coincides, this does not always lead to similar results. Thus, the dates with strong winds in Aniva Bay and southeastern Sakhalin coast often concurred, however, they did not equally affect the formation of pink salmon abundance in these areas because of different timing of fry migrations (Kaev 2018). When reporting regional characteristics of the negative cyclonic impact on pink salmon reproduction, we should also note that in southern areas this impact was mainly manifested through the storms in the juvenile feeding period, and in northern areas it manifested through the soil erosion on spawning grounds during floods.

Thus, a decline of pink salmon abundance in broodlines appeared under the impact of strong cyclones during fish embryonal development in rivers (destruction of redds) or in the period of mass fry migration to seawaters, allowing us to suggest their significant importance for abundance formation of this species. The appearance of low-harvest broodlines series was observed to coincide by time with the change of warm zonal and cold meridian epochs which have been observed in the 1980s and hypothetically occur in the contemporary period (Kotenev et al. 2012, 2015). Perhaps, a change of these epochs is accompanied by the shift of trajectories and dates of cyclones passing. So, in these years the probability of their negative impact on pink salmon reproduction increases, resulting in a series of the low-harvest broodlines. At the same time the typhoons’ strength and limits of their impact vary continuously that explains the appearance of local characteristics for pink salmon changes in abundance in the region.

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What Formed the Pacific Salmon Biomass in Amur River Basin in 2000–2010s?

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Keywords: Amur River, Pacific salmon, commercial catch, abundance dynamics, escapement

The Amur River is the biggest salmon basin in Asia, and the tenth longest river in the world. It is 5,052 km in length, from the source of the Kerulen River (Mongolia) and further along Lake Dalainor and the Argun River. The area of Amur basin (1,855 km²) is larger than the area of the Sea of Okhotsk (1,600 km²), which the Amur River enters.

Commercial catch data for all species of Amur River Pacific salmon shows the same trend: a sharp peak of catches in the 1910s and the subsequent decline to minimum catches in the early 2000s, and a sharp peak again, 100 years later, in the 2010s (Fig. 1–3). What processes could support such strong rise in the number of three ecologically different groups of Pacific salmon in Amur basin?

Fig. 1. Fall chum commercial catches in Amur River, 1907–2017.

Fig. 2. Summer chum commercial catches in Amur River, 1907–2017.

Fig. 3. Pink salmon commercial catches in Amur River, 1907–2017.

Fig. 4. Pink and chum salmon escapement in the Duki test river (Amur basin) during 1984–2005 (Amurrybvod’s data).

In 1990s the numbers of pink salmon, summer, and fall chum salmon in the Amur River were low and they could not form very large generations. The small parent generation for pink and chum salmon led to low abundance of progeny. Commercial catches of pink salmon, summer, and fall chum salmon in the Amur River during 1990–2005 were as small as 2,000–5,000 metric tons each.
After 2005, the number of Pacific salmon in the Amur River began to grow. Commercial catches of each species reached 5,000 metric tons in 2009, and quickly exceeded 10,000 metric tons. In 2016, the catches of pink salmon reached a new historical maximum 23,100 metric tons. At the same time, the escapement graph from the test Duki River declined for all species of Amur River Pacific salmon, and in 1998 reached a minimum, which continued past 2005 (Fig. 4).

Which factor prevailed for the formation of the of Amur River salmon biomass? It is unlikely that hatchery reproduction could affect the Amur River Pacific salmon population when there was such a small contribution of hatchery fry compared to natural processes (Belyaev and Zolotukhin 2000) (Fig. 5). It is also unlikely that the Amur River Pacific salmon populations could be affected by changes in the average surface air temperature, as the first peak of their abundance occurred when the negative anomalies were at a maximum in 1900–1910s. The second peak in abundance of Amur River salmon occurred when the positive surface air temperature anomalies were at a maximum in 2000–2010s (Fig. 6).

![Fig. 5. Number of wild and hatchery chum salmon fry in Amur River during 1987–1999, million. Dotted line—wild chum salmon fry; solid line—hatchery chum salmon fry.](image1)

![Fig. 6. Land and Ocean surface mean temperature anomalies, 1880–2012. NOAA data.](image2)

The mortality rate for the Amur River Pacific salmon continued to be small in 2015: gill net traumas were 0.1%, traumas from Alepisaurus ferox and other predator fish were about 1.8%, and traumas from long line hooks were 0.1% in the Amur River. These values are lower than the mortalities from 1994–2000 (Zolotukhin and Kaplanova 2002). It is most likely that abundance of the Amur River Pacific salmon generations is regulated within estuaries and in the early marine periods, when the juvenile mortality rate is increased by the ice presence and ice movement into the coastal zone. Dynamics of the Sea of Okhotsk ice cover is similar to the dynamics of solar cycles (Wolf’s numbers) (Shuntov 2001), but their impact on the Amur salmon juveniles number is mediated by complex of environmental and climatic factors. The resulting impact of Sea of Okhotsk ice cover is heavily influenced by the survival rate of the Amur River Pacific salmon during ocean migration, which has the highest weight among other environmental and climatic factors. Most good Pearson’s correlation for some climate indexes and total commercial chum salmon catch in the Amur River during 1990–2017 were: North Pacific Circulation PCI 0.6471, and Global Air Temperature GLB.Ts+dSST -0.4952. Other indexes had small power: AFI (-0.0478), ALPI (-0.1709), NP (0.1382), N. HEMI (-0.2759), PDO (0.0358), LOD (0.2074), Wolf’s numbers (-0.2402).

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Geographical Origins of Juvenile Chum Salmon Migrating Along the Pacific Coast of Hokkaido, Japan, During Early Summer

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Keywords: juvenile chum salmon, migration route, otolith marking, genetic stock identification

Japanese chum salmon migrate globally, from their natal river to the Gulf of Alaska via Okhotsk Sea, Northwest Pacific Ocean, and Bering Sea depending on their life stage and season (Urawa 2004; Urawa et al. 2018). Irie (1990) illustrated a map showing the migration route of juvenile chum salmon along the coastal waters of northern Japan, and the map was updated by Urawa et al. (2018). On the eastern Pacific coast of Hokkaido region (off Konbumori) there was a mixed community of juvenile chum salmon from the nearest and distinct rivers (Hasegawa et al. 2013), which was mainly composed of Pacific coast of Hokkaido and Honshu stocks (Sato et al. 2013). The present study was conducted to examine the origins of juvenile chum salmon migrating along the western and eastern Pacific coasts of Hokkaido by otolith marking and genetic stock identification analyses.

Juvenile chum salmon were captured at set nets in Muroran, Kojohama, Atsuga, and Harutachi coasts along the western Pacific coast of Hokkaido and at the four or five sampling stations (0.4–12 km offshore Konbumori) in the eastern Pacific coast of Hokkaido, during May to July of 2013–2016 (Fig. 1). Fish samples were collected by dip nets at the set nets and by a seine net towed by two boats at stations off Konbumori. Otolith and genetic samples were collected from each juvenile chum salmon after measurement of fork length (FL) and body weight. Otolith samples were examined for the presence of thermal marks and the hatchery origins were determined using specific thermal mark patterns. As for genetic samples, after DNA extraction, each sample was assayed for 45 single nucleotide polymorphism (SNP) loci using TaqMan chemistry (Sato et al. 2013). Five regional stock contributions (Hokkaido: Japan Sea coast, Okhotsk Sea/Nemuro Strait, and Pacific coast; Honshu: Pacific coast and Japan Sea coast) were estimated by a conditional maximum likelihood using a SNP baseline dataset from 57 populations (Sato et al. 2014) and an additional 24 populations (Sato et al. unpublished data). Furthermore, the weighted mean composition of five regional stocks was calculated in each survey area.

Fig. 1. Sampling locations of juvenile chum salmon along the Pacific coast of Hokkaido, Japan, during 2013–2016. Fish samples were collected at four or five stations (0.4–12 km from shore) in the Konbumori coast, but do not show detail in this figure.
A total of 14,535 fish were collected in the Pacific coastal waters of Hokkaido in the spring and early summer of 2013–2016. The mean FL of juvenile chum salmon collected in Muroran and Kojohama coasts were 66.7±12.0 mm and 72.9±12.1 mm, respectively, while the mean FL of juvenile fish caught in Atsuga and Harutachi coasts were 96.1±52.2 mm and 93.1±11.2 mm, respectively. In Konbumori coast, the mean FL of juvenile chum salmon was 78.8±14.4 mm.

In the western Pacific coasts, 1,773 out of 12,098 juvenile chum salmon were otolith-marked fish, of which 1,639 juveniles (92.4%) originated from hatcheries along the western Pacific coast of Hokkaido, and 104 and one otolith-marked juvenile chum salmon were released from hatcheries along the eastern Pacific coast of Hokkaido and Nemuro Strait, respectively. In the Konbumori coast of eastern Pacific, 593 out of 2,437 samples (24.3%) were otolith-marked fish, of which 558 and 33 juveniles were released from hatcheries along the eastern and western Pacific coast of Hokkaido, respectively. Residual two otolith-marked chum salmon juvenile were originated from Oirase (Aomori Prefecture) and a hatchery in Iwate Prefecture along the Pacific coast of Honshu. A total of 31 otolith-marked juvenile chum salmon, which originated from hatcheries along the Pacific and Japan Sea coasts in Honshu, were collected from the all survey areas except the Muroran coast during 2013–2015 seasons. The mean FL of otolith-marked juvenile fish from Pacific and Japan Sea coasts of Honshu were 112.6±12.4 mm and 137.7±13.2 mm, respectively. Sixteen of the otolith-marked chum salmon juveniles originated from five hatcheries (Oirase, Orikasa, Shimoakka, Taro, and Tsugaruishi) along the Pacific coast of Honshu, while 11 other otolith-marked fish were released from hatcheries in Iwate Prefecture. Four otolith-marked fish originated from Oirase (Aomori Prefecture) and Kawabukuro (Akita Prefecture) hatcheries along the Japan Sea coast of Honshu. Twenty-four out of 31 otolith-marked juvenile fish from Honshu hatcheries (21 individuals from Pacific coast and three individuals from Japan Sea coast) were collected in Harutachi coast. No otolith-marked fish released from Honshu hatcheries were caught in 2016. The mean FL of otolith-marked fish originated from Hokkaido hatcheries was under 100 mm (Nemuro Strait: 94.6 mm, western Pacific coast: 87.3±17.4 mm, eastern Pacific coast: 75.7±8.7 mm), while that from Honshu hatcheries was significantly larger than Hokkaido fish (Tukey’s test, p < 0.05).

The genetic stock identification suggested that the weighted mean stock compositions of small size fish (<100 mm in FL) caught in all survey areas were 82.5–99.4% Hokkaido stocks (range: 2.1–11.1% Japan Sea coast, 18.2–26.5% Okhotsk Sea/Nemuro Strait, and 48.4–9.0% Pacific coast stocks) and 0.6–17.5% Honshu stocks (range: 0.6–5.7% Pacific coast and 0.0–11.8% Japan Sea coast). The Pacific coast Hokkaido stocks were most dominant in all survey areas. The weighted means of estimated stock composition of large size fish (≥100 mm in FL) collected in Kojohama, Atsuga, Harutachi, and Konbumori were 57.7–71.6% Hokkaido stocks (range: 0.0–2.4% Japan Sea coast, 0.0–13.7% Okhotsk Sea/Nemuro Strait, and 41.5–71.6% Pacific coast stocks) and 28.4–42.3% Honshu stocks (range: 8.6–32.0% Pacific coast and 0.6–20.7% Japan Sea coast stocks). In the 2016 season, however, the proportion of Pacific and Japan Sea coasts of Honshu stocks were 7.8–17.0% and 0.0–8.0% in Harutachi and Konbumori coasts, respectively.

Otolith-marked juvenile chum salmon released from hatcheries along the western Pacific coast in Hokkaido were the most dominant in the western Pacific coast in Hokkaido. In addition, several otolith-marked juvenile fish originating from the eastern Pacific coast in Hokkaido were collected at the same areas. A previous study also demonstrated that juvenile chum salmon of the eastern Pacific coast of Hokkaido stocks (Tokachi and Kushiro rivers) migrated westward to the western Pacific coast in Hokkaido (Saito et al. 2013).

The present study confirmed that otolith-marked fish released from the Pacific and Japan Sea coasts in Honshu were present along the western Pacific coast in Hokkaido. Particularly, most of the Pacific coast Honshu stocks were collected in Hidaka (Harutachi). These findings suggest that juvenile chum salmon that originated from the Pacific coast of Honshu may reach the western Pacific coast (Hidaka coast) and then migrate west or eastward along the Pacific coast in Hokkaido. In addition, some juvenile chum salmon originating from the Japan Sea coast of Honshu also migrate along the Pacific coast of Hokkaido through the Tugaru Strait. These migration routes were also simulated by a hydrodynamic model (Azumaya et al. in press).

Our results indicated that the mean FL of otolith-marked juvenile chum salmon from Honshu was significantly higher than that of the Hokkaido stocks. The genetic stock identification also suggests the composition of the Pacific coast of Honshu stocks was relatively higher in the large juvenile chum salmon group (FL ≥ 100 mm) than the small fish group (FL < 100 mm). A previous study indicated that juvenile chum salmon migrating from distant rivers with achievement of a certain growth rate had better survival and were able to arrive the eastern Pacific coast in Hokkaido (Honda et al. 2017). The present results may support this hypothesis.

No otolith-marked fish released from Honshu hatcheries were caught in 2016. Stock composition of juvenile chum salmon originated from the Pacific coast of Honshu in 2016 was also lower than that of 2013–2015 seasons. During early-May to late-June in 2016, the surface seawater temperature (SST) anomalies of Pacific coast around
Hokkaido and Honshu indicated were approximately 2–5°C higher (data source: Japan Meteorological Agency, www.jma.go.jp/jma/index.html). This unfavorable ocean condition might affect the migration and survival of juvenile fish in 2016.

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Growth Rate Characteristics during Early Marine Life and Sea-entry Conditions of Juvenile Chum Salmon Originating from Two Rivers along the Pacific Coast of Hokkaido, Japan

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Keywords: early marine life, growth rate, otolith daily growth increments, sea-entry condition

Juvenile chum salmon originating from rivers along the Pacific coast of Hokkaido, Japan migrate northwards to the Sea of Okhotsk, typically passing off the easternmost part of Hokkaido (Irie 1990; Chistyakova and Bugaev 2013). Japanese juvenile chum salmon are likely to undergo growth-dependent mortality (Honda et al. 2017, 2018). Thus, understanding a suitable release timing and body size to make fish grow faster after sea entry is desired, to improve release strategies from Japanese hatcheries.

In this study, juvenile chum salmon originating from the Tokachi (42°41’N, 143°40’E) and Yurappu (42°16’N, 140°17’E) rivers consisting of three sampling-year groups each [2005 (n = 23, 72.0–90.0 mm FL), 2007 (n = 34, 72.0–107.1 mm FL), and 2009 (n = 34, 64.0–94.0 mm FL) for Tokachi and 2013 (n = 27, 93.5–113.9 mm FL), 2014 (n = 31, 92.2–115.9 mm FL), and 2016 (n = 25, 91.9–104.6 mm FL) for Yurappu] sampled in June–July at Konbumori (42°50’N, 144°34’E; ~80 km northeast of the Tokachi river mouth) and at Atsuga or Harutachi (42°15’–24’N, 142°12’–29’E; ~150–180 km east of the Yurappu river mouth), respectively, were used. We examined the relationship for each group between back-calculated growth rate (mean daily growth in FL) during early marine life of juvenile chum salmon and their estimated dates and FLs at sea entry, using daily-increment analysis of otoliths (see Honda et al. 2017 for methodology).

Average (± SD) growth rates of Tokachi specimens were 0.57 ± 0.11 mm/day, 0.61 ± 0.11 mm/day, and 0.55 ± 0.08 mm/day for groups sampled in 2005, 2007, and 2009, respectively, whereas those of Yurappu specimens were 1.06 ± 0.11 mm/day, 0.99 ± 0.11 mm/day, and 0.88 ± 0.08 mm/day for groups sampled in 2013, 2014, and 2016. Any remarkable trends were not found in the relationships between growth rates and dates and FLs at sea entry for each sampling-year group except for the 2005-Tokachi group of which fish that migrated to the sea later showed relatively higher growth rate. Growth rates of Yurappu specimens were even higher than those originating from the same river sampled at Konbumori (~400 km east of the Yurappu river mouth) during 2005–2014 (0.71 ± 0.12 mm/day, n = 27) estimated by Honda et al. (2017). The few remarkable relationships between growth rate and date and FL at sea entry were possibly a result of our small sample size and/or from the fact that we only sampled fish selected through growth-dependent survival mechanisms during earlier marine life. Moreover, higher growth rates observed by Yurappu specimens particularly those sampled in 2013 and 2014, which are being assumed as poor-return stocks (Watanabe et al. 2018), may suggest that only fish with such high growth rates could survive even in years when massive mortality took place.

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Biology of Juvenile Ozernovskaya Sockeye Salmon *Oncorhynchus nerka* (the Ozernaya River, Basin of the Kurilskoe Lake) during Downstream Migration and Early Marine Period of Life

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**Fig. 1.** Kurilskoe Lake and Ozernaya River with scheme of hydrology-morphological and biological stations conducted June–August 2017.

Ozernovskaya sockeye salmon is the largest and the most studied population of Asian sockeye salmon, spawning in the basin of Ozernaya River and Kurilskoe Lake (South Kamchatka)¹. In the 1930s, results of studying this population were generalized for the first time (Krokhin and Krogius 1937), and since 1940, monitoring research has been provided (Anon 2010; Koval et al. 2014). During this period the biology of Ozernovskaya sockeye salmon in the course of spawning, juvenile foraging in the Kurilskoe Lake (before migration into the Ozernaya River), the marine period of life, and spawning migration has been determined (Bugaev 1995, 2011; Bugaev et al. 2009). Yet,

¹ The basin and estuary area of the Ozernaya River are located outside south and south-west of the Kamchatka Peninsula. The river outflows from Kurilskoe Lake and inflows to the Okhotsk Sea (see Fig. 1). The length of the Kurilskoe Lake is ~12.4 km, its width is ~10.6 km, its area is ~76 km², its volume is ~14.2 km³, its height of the surface above sea level is ~81 m. The lake has a deep hollow (~ 300 m), located between several active volcanoes. The length of the Ozernaya River is ~45 km, its vertical drop from the head to the mouth is ~80 m; the channel of the river is weakly branched, with a stepped bed in the up reach and with numerous rapids in the low reach. The average annual water discharge (13 km upstream from the river mouth) is 48.9 m³/s (1976–2003). At the mouth of the Ozernaya River is located at Ozernovsky Village—the main center of the sockeye salmon fishery in the Russian Far East.
until recently the biology during juvenile downstream migration and early marine period has been poorly understood, although it is known that for some Pacific salmon species (i.e., pink and chum salmon) migrations and period in estuaries and nearshore are the most critical periods of life, forming generation abundance (Karpenko 1998; Levings 2016). A high mortality of juvenile salmon during these periods of their life history makes it difficult to forecast adult returns, which are necessary for efficient stock management and sustainable fishing (Shevlyakov and Koval 2012).

An integrated field study of juvenile ozernovskaya sockeye salmon in the basin of Kurilskoe Lake, the Ozernaya River estuary and coastal waters of the Okhotsk Sea was carried out from June–August 2017 (Fig. 1). The field hydrological and morphological studies were completed using standard methods (Anon 1993; Federal Scientific Research Institute of Fisheries and Oceanography 2011). This included measuring water depth (Kurilskoe Lake, Ozernaya River estuary and coastal waters of the Okhotsk Sea), monitoring the water level, temperature, and salinity at seven stationary hydrological stations (lower reach and estuary of the Ozernaya River, coastal waters of the Okhotsk Sea), measuring speed and direction of the current, and water discharge (Ozernaya River), and hydrological surveys, which measured temperature, salinity, PH, turbidity, chlorophyll-a, dissolved oxygen, and illumination (Kurilskoe Lake, Ozernaya River, coastal waters of the Okhotsk Sea). Measuring the hydrological characteristics of the environment was completed using the autonomous devices GMU–2 and STD (CDB GMP, Obninsk), DST centi–TD, DST tilt, DST CT (Star–Oddi Ltd.) and multiparameter probe AAQ–RINKO Profiler (JFE Advantech Ltd.).

The distribution of the juvenile fish in the waters of Kurilskoe Lake was studied and biological data was obtained with the use of the BioSonics DT–X scientific echosounder, gillnets (with mesh size 18 mm) and 3/8 m fingerling seine, in the basin of the Ozernaya River; fingerling seine (river and estuary) and beam–trawl 2.6/8.2 m (estuary), in the coastal waters of the Okhotsk Sea; beam–trawl (the mesh size in the cod-end of the seine and trawl was 4 mm).

Fig. 2. Estuary of the Ozernaya River and dynamics of some hydrological characteristics (~1 km from river mouth) from 16 June to 25 July 2017.
The methods of the hydroacoustics observations and of the control catches was described in detail earlier (Koval et al. 2012; 2013). The seine survey from the head to the mouth of the Ozernaya River was carried out during the day on 16 June 2017 (the distance between the stations of seining was 3 km). During the survey, the fish were caught in different river biotopes (middle pelagic zone, littoral zone, pelagic zone of river creeks and channels). After that the survey, the control seining was carried out during the day in the littoral zone of the Ozernaya River estuary at the same station that was placed in the river ~1 km upstream from the river mouth, once per five days from 20 June to 25 July 2017 (Fig. 2). The trawl fishing in the Ozernaya River estuary and coastal waters of the Okhotsk Sea was carried out on 1, 6, 17, 18, and 23 July 2017. All control fishing operations were carried out with simultaneous measuring of main environmental abiotic parameters with the AAQ–RINKO Profiler probe. More than 1,000 hydrological, 23 gillnet, 60 seine, and 20 trawl stations were conducted during the period of our field research. The distance of the hydroacoustics tracks in the Kurilskoe Lake was 262 km.

The main goal we had set in the framework of this study was to estimate the role of the downstream migration and early marine period of life in the formation of the stock abundance of Ozernovskaya sockeye salmon. For this goal, in addition to the results of our field study in 2017, we also used: 1) data on the abundance and biological characteristics of juvenile Ozernovskaya sockeye salmon, migrated from Kurilskoe Lake (obtained by workers of KamchatNIRO at the Ozernovsk Biological Station placed at the head of the Ozernaya River); 2) results of trawl surveys by KamchatNIRO in coastal waters of the West Kamchatka (conducted since 2004) (Koval et al. 2011); 3) data of forecasts of adult sockeye salmon returns into the Ozernaya River basin for last 10 years.

It is now known that in the first year of life, after leaving the redds, juvenile Ozernovskaya sockeye salmon emigrate from the lake spawning grounds (and from the lake tributaries) for pelagic foraging in Kurilskoe Lake (Bugaev et al. 2009; Kirillova et al. 2015). The most abundant underyearling sockeye salmon are from river spawning grounds (placed in the up reach of the Ozernaya River), they also migrate into the lake for foraging, while a minor part migrate downstream to the river mouth (where they create aggregations normally in July) (Kirillova et al. 2014; 2017; Pavlov et al. 2015). In the Kurilskoe Lake, juvenile sockeye salmon can stay for foraging from one to three years (very rarely—four) before leaving for the sea. The dominance among the smolts (70–90%) is the group age of 2+. The downstream migration of sockeye salmon smolts down the Ozernaya River starts in late May or early June and stops in the last half of July or early August. The fish usually migrate at night, and the migration mainly stops at dawn (Bugaev et al. 2009). Juvenile sockeye salmon of different ages occupy different biotopes in the Ozernaya River: underyearlings inhabit in the littoral zone near the shores with weak currents, and smolts occur in the midstream of the water flows (Kirillova et al. 2014). A small abundance of underyearling sockeye salmon can leave the river for the sea (Pavlov et al. 2015), but these fish have been never been recorded in adult returns into the basin of the Ozernaya River.

The results of our field study from June–August 2017 indicated, that for the research period the Ozernaya River passed the period of high flows (in the inlet a water discharge was >60 m³/sec). A flood during high water period began in mid-May and reached its peak on 20 June. During flood recession (in July) there were several weak and one strong (25–27 July) rain floods. As a result, in August, the water discharge of the river decreased. The speed of the current on the river mainstream was more than 1.0–1.5 m/sec.

The Ozernaya River estuary is a small and shallow-water object (length ~1.6 km; width up to 200–300 m; depth <1.0–1.5 m; see Fig. 2). It is connected with the sea through a narrow (~30 m) and short (150 m) channel (hereinafter «inlet»). Marine tides near the Ozernaya River mouth are irregular, once half a day, from 1 m in the neap tide and up to 2.2 m in spring tide. On entering the estuary, the tides quickly vanish: never more than 40% from initial value; just 0.8 km inland from the sea. The tides never reached 6 km inland from the sea, where the first river rapids are. The water current in the inlet in summer was directed toward the sea no matter the tidal phase, and the maximal speed of the flow at low tide was 1.9–2.5 m/sec. At high tide the speed decreased but was anyway high (1.1–1.7 m/sec). In summer 2017, the water in the estuary was permanently fresh. Slight occurrence of salty waters in the inlet began in the last days of August when the river flow was reduced to 45 m³/sec. With this connection and considering the long-term characteristics of the Ozernaya River flow, the salinization of the estuary in the summer period is a very rare and short phenomenon. It cannot occur every year and only on days of very poor water discharges. In most cases the saline waters enter the estuary for several hours, and the square of salinization covers just few hundred meters from the sea.
Fig. 3. Dynamics of downstream migration of sockeye salmon smolts from Kurilskoe Lake, June–July 2017 (according to control catches in head of the Ozernaya River).

On the catch data of the control trap in the head of the Ozernaya River, the downstream migration of juvenile sockeye salmon from Kurilskoe Lake in 2017 began on 1 June and was over on 19 July (Fig. 3). From the results of calculations (provided on the base of control trap catches) it was found that 3.255\textsuperscript{2} million sockeye salmon smolts migrated to the lake for this period. The maximal number of migrants was observed on 19 June (0.428 million fishes) and on 5 July (0.275 million fishes). The migrants abundance on the other days usually did not exceed 0.100–0.200 million fishes. The portion of fish of age group 2+ was 94.0% in the total number of the smolts, and the portions of 1+ and 3+ fishes were 1.8% and 4.2% respectively. The maximal length (AC) and weight of smolts in the control trap catches from 10 June to 10 July varied from 7.0 to 10.4 cm, and from 2.39 to 9.53 g (averaged 8.3 cm and 5.41 g) (\(n=400\)). The average body length and weight of the smolts 1+ was 7.9 cm and 4.92 g (\(n=7\)); 2+ – 8.3 cm and 5.34 g (\(n=376\)); 3+ – 9.1 cm and 7.22 g (\(n=17\)).

Fig. 4. Distribution of abundance (ind.) and average length (cm) of sockeye salmon smolts in seine catches in the Ozernaya River (16 June 2017) and in trawl catches (6 July 2017) in coastal waters of the Okhotsk Sea.

\textsuperscript{2} It should be understood, that this estimate is relative, not absolute (the same applies for estimates of fish abundance by data of trawl surveys, see below). Such indicators can be used to characterize abundance for different generations only in a comparative aspect–based on long-term series data.
At all 15-ht stations, used during the seine survey in the Ozernaya River 16 June 2017 (during the mass migration of juvenile sockeye salmon from Kurilskoe Lake), 4449 juveniles of chum salmon (94.0%), 153 sockeye salmon smolts (3.2%) (Fig. 4), 59 juveniles of Dolly Varden (1.3%), 42 (0.9%) juveniles of coho and 4 (<0.1%) of pink salmon were caught. At the station №15, placed in Ozernaya River estuary (~1 km from the inlet, see Fig. 2), there were diadromous starry flounder (20 individuals) and threespine stickleback (4 individuals) found in the catches. Sockeye salmon smolts in the Ozernaya River were observed mostly in the mainstream (where the average speed of water current was ~1 m/sec or greater), and in the pelagic zones of river backwaters and channels (where the water current is slow). In such areas of the river, the total portion of smolts was 13.0% of the total number of catches. At the same time, juvenile individuals of other salmon species were observed everywhere in the littoral zone (where speed of the current was not >0.3 m/sec). Sockeye salmon smolts were sporadic at such areas (0.3%).

The body length and weight of sockeye salmon smolts in the seine catches was 6.8–10.1 cm (8.0 cm) and 2.23–9.16 g (4.17 g) respectively.

In littoral zone of the Ozernaya River estuary (at base station ~1 km inland from the inlet, see Fig. 2) at 8-ht seine fishing operations (carried out from 20 June to 25 July, 2017) 3710 juveniles of chum salmon (96.6%), 58 underyearling sockeye salmon (1.5%), 45 coho salmon (1.2%), 12 Dolly Varden (0.3%), 7 three spine stickleback (0.2%), and 1 starry flounder (<0.1%) were caught. There were no sockeye salmon smolts in the catches. Underyearling sockeye were sporadic in the estuary after 5 July, and their number in the catches increased (the maximal number—31 individuals were caught on 15 July). The body length of under-yearlings ranged from 2.8–4.2 cm (averaging 3.4 cm), and the weight of under-yearlings ranged from 0.13–0.60 g (averaging 0.30 g). As indicated by the data, juvenile chum salmon predominated in the catches in the littoral zone of mainstream and estuary of the Ozernaya River during observation period, which corresponds with the data of previous studies (Kirillova et al. 2014; 2017; Pavlov et al. 2015).

At 2-ht trawl stations, conducted in the pelagic zone of the Ozernaya River estuary during the day on 1 and 17 July 2017, nine chum salmon juveniles were caught. In the coastal waters of the Okhotsk Sea, adjacent to the Ozernaya River mouth, the invertebrates (jellyfish and mysids) were the dominant species caught in the trawls, while juvenile fish were sporadic (indicating that the fish could escape the trawl). The total catch at 18-ht trawl stations, conducted from marine side adjacent to the Ozernaya River mouth, included 2 smolts of sockeye salmon (caught on 6 July 2017) and two smolts of chum salmon (caught on 17 and 18 July 2018). These fish were caught at the stations placed ~2.5–3.0 km northward from the river mouth (Fig. 4). The body length and weight of the sockeye salmon smolts caught in the trawls was 7.4–7.8 cm (averaging 7.6 cm) and 3.40–4.12 g (averaging 3.76 g).

It was previously thought, that sockeye salmon smolts migrated from the head to mouth of the Ozernaya River over a period of 5–10 days (Bugaev et al. 2009). Our results indicate that the period of their migration can be much shorter. Considering the distance from the head to mouth of the Ozernaya River (~45 km), the average speed of water current in the mainstream (~1 m/sec) and the stable speed of swimming fish (approximately 0.5 m/s for juvenile sockeye salmon; Bell, 1986), the period to emigrate from the river head to mouth is about 7 hours. The dark time on the latitude of the Ozernaya River during the sockeye salmon migration is 7.5–8 hours. In this way the majority of sockeye salmon smolts emigrating from Kurilskoe Lake over 24 hours, can reach the coastal waters of the Okhotsk Sea during the night3. Only those migrants which failed to reach the sea in one night can be seen in the river during the day time. That could be because juvenile sockeye salmon, migrated from Kurilskoe Lake passed smoltification and have already adapted to pelagic way of life. The fish are poorly adapted to stay in the hydrological conditions of the Ozernaya River, and therefore quickly leave the river for pelagic foraging in coastal waters of the Okhotsk Sea. Moreover, the fish, which a stay in the low reach of the river in day time, strive for the lake-type biotopes (i.e., the pelagic zone of the river backwaters, inlets and channels with a weak stream). It should be noted that similar features in the biology of sockeye salmon smolts during downstream migration from lakes in other areas of reproduction have also been observed (Hartman et al. 1967).

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3 Such conclusion can be confirmed by results of study on the speed of the migration of sockeye salmon smolts in the basin of the Fraser River (British Columbia), which can reach from ~50 to ~220 km per day (Clark et al. 2016).
The following is from analysis of stomach contents of sockeye salmon smolts (n=34) during their migration in the Ozernaya River, where the fish are feeding intensely (Fig. 5). During the seine survey on 16 June 2017, the stomach fullness indexes (SFI) of some smolts in the river were 500–700/ooo, and averaged 204.1/ooo. There were no smolts with empty stomachs in the samples. The main prey item in pelagic zone of the Kurilskoe Lake for juvenile sockeye salmon was planktonic *Cyclops scutifer* (less often—*Daphnia longiremis*) (Bugaev et al. 2009), during the migration the fish were feeding on the larval and imago amphibian insects (Ephemeroptera, Plecoptera, Chironomidae, etc.). Imago, larvae and pupas of various terrestrial insects and *C. scutifer*, washed out of Kurilskoe Lake into the Ozernaya River (especially during the floods) can make up a huge part of the smolts’ diet (Kirillova et al. 2015). Most likely, *C. scutifer* become concentrated in the biotopes which have a weak current, and are preferred by sockeye salmon smolts which failed to emigrate quick. Residuals of juvenile fish were found in stomachs of sockeye salmon smolts in the lower reaches of the river. On entering the sea, juvenile sockeye salmon immediately changed their diet, and started to consume marine zooplankton—regular food during their sea life (Karpenko et al. 2013), although some residuals of river food can still be found in their stomachs (like imago of Diptera) (Fig. 2).

After downstream migration in the river, sockeye salmon smolts enter the Ozernaya River estuary. As it was mentioned above, in summer 2017 the hydrological conditions there were quite stable and very similar to conditions in the river. This is why in the summer season the Ozernaya River estuary is the area inhabited by juvenile fish of various salmonid species, some of these species use it as their feeding and nursery grounds before leaving for the sea (chum and coho salmon, Dolly Varden) and the other species use it as a transit zone before their up-stream migration in the river (coho salmon and Dolly Varden) (Pavlov et al. 2015; our data). At the same time, according to our data, the estuary is a transit area for the sockeye salmon smolts. The smolts don’t stay there, instead they leave for the sea immediately. Juvenile salmonids from the Ozernaya River can leave for the sea irrespective of ebb tide phase, and the fish which entered the coastal waters never come back into the river (Pavlov et al. 2015). The other fish species are quite abundant in estuaries of the West Kamchatka in summer season (threespine stickleback and starry flounder), and from time to time can enter the site from the Okhotsk Sea with the tides due to the hydrological specifics of the Ozernaya River estuary.

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4 For the period of our observations (from 5 July to 25 July 2017), in the Ozernaya River estuary there was only a slight increase in the water turbidity which was correlated with the rainfalls floods during the period this occurred (see Fig. 2).
The hydrological surveys, carried out in the coastal waters of the Okhotsk Sea in July 2017, have indicated that there is a formation of a huge zone of mixing the river and marine waters in summer months in the waters adjacent to the inlet of the Ozernaya River (Fig. 6). The «core» of this zone (with salinity gradient from 0 to 15–20‰ and temperature from 6 to 8°C) is placed in vicinity of the river inlet. The water there is well mixed vertically, and therefore horizontal temperature and salinity gradients dominate in this area of the seaside. Seaward from the «core» there is much longer «peripheral» part of the mixing zone with salinity gradient from 15–20‰ to 31–32‰ and the temperatures from 8 to 11°C. A thin layer (up to ~0.5 m) of freshened water covers the sea water. In July 2017, due to the permanent flow of the river water the mixing zone at sea enlarged, and the outer edges moved away (Fig. 6). Enlarging the zone went in two directions: northward along the coast (for a distance up to 10–15 km) and eastward from the coast (up to 5–7 km). By late July, the mixing zone from the flow of the Ozernaya River had joined with the mixing zones of other rivers, moving it north.

The data obtained confirms that in the summer season (especially in the high-water years) on the West Kamchatka a narrow (width of several kilometers), but very long (possibly up to several hundred kilometers) freshened zone can be formed, uniting inlet areas of several rivers in this region. This is due to the effect of freshening continental flow, greatly increased during spring and summer floods. The other peculiarity of this area is that in June–August the southern part of the coast of West Kamchatka is influenced by the Pacific Ocean waters, transformed and cooled in the Kuril straits. This is why the water temperature increases northward from Cape Lopatka, and the most warmed area of the West Kamchatkan shelf is between 52 and 56° N (the difference between the temperatures on the south and in the central part of this area can reach 2–3°C) (Anon 1998).

On the long-term data of the trawl surveys by KamchatNIRO, the catches of juvenile salmon (including sockeye salmon) on the southwest coast of Kamchatka are always maximal at the surface water temperatures ranged as 10–13°C. The major schools of the juvenile fish are usually connected to the mouths of big rivers (Ozernaya, Opala, Bolshaya, Kihchik, Pynta, Kol’ et al.), from there the salmon smolts usually migrate northward. The main abundance of sockeye salmon juveniles, foraging on the West Kamchatkan shelf, is formed by Ozernovskaya sockeye salmon, as it is the most abundant population in mentioned area (Koval et al. 2011).

As shown in Fig. 7, during the trawl survey, conducted from 30 July to 11 August 2017, the water temperature in the coastal waters of the Okhotsk Sea at the same latitude as the Ozernaya River was <10°C. The major schools of juvenile sockeye salmon (97% of total sockeye abundance in trawl catches) were observed at the stations north of the river mouth, in the area where the surface temperatures were 10–13°C. Analysis of the dynamics of body length and weight of the smolts which migrated from Kurilskoe Lake to the trawl survey in 2017 has indicated that the average daily growth of juvenile Ozernovskaya sockeye salmon at sea can be 0.14–0.15 cm (1.1–1.2% of the body length) and 0.7–0.8 g (3.0–3.1% of the body weight). As a result, after one month of sea foraging, the body length can increase ~1.5 times, and the weight ~5 times.

5 Apparently, this temperature is optimal and provides the most effective energy metabolism of the organism and the highest growth rate of Pacific salmon juveniles (Karpenko et al., 2013).
Fig. 7. Distribution of surface water temperature (°C), abundance (ind.) and average length (cm) of juvenile sockeye salmon (by data of trawl survey conducted in coastal waters of the Okhotsk Sea, 30 July–11 August 2017).

Fig. 8. Total abundance of smolts migrated from Kurilskoe Lake (June–July) and total abundance of sockeye salmon juveniles estimated on trawl surveys at coastal waters of the Okhotsk sea (July–August), 2004–2017 (Fig. 8a); Correlation between these two indicators (Fig. 8b).
Thus, environmental conditions existing during the period of downstream migration and the early marine period of life of Ozernovskaya sockeye salmon can play a very important role in their biology. The geographical position of the Ozernaya River basin and the hydrological regime in the channel and estuary of this river can determine the speed of the migration of sockeye salmon smolts from Kurilskoe Lake to the sea. As a result, there is low mortality from riverine predators (Hartman et al. 1967; Clark et al. 2016), which are also practically absent in the basin of the Ozernaya River during the smolts migration, based on our observations. The temperature regime in the coastal waters of West Kamchatka predetermines the general direction of juvenile migration in the first months of sea life and provides conditions for a high growth rate and a quick escape from the pressure of various marine predators (it is likely that areas with the higher water temperatures are more favorable for fish to find food resources). Furthermore, the extended zone of freshening sea can promote effective restructuring of osmoregulation and adaptation of fish on the transit from freshwater to marine period of life. As Ozernovskaya sockeye salmon migrate to sea when they are quite big (the body length 7–10 cm) and ready to live in pelagic habitat (can immediately start to consume energy-valuable marine food, which also contributes into the growth rate increase), the total survival in the early marine period should be quite high.

As a result, as illustrated in Fig. 8, the total relative abundance of juvenile sockeye salmon, counted in the coastal waters near the southwest Kamchatka coast (calculated on the data by trawl surveys in 2005, 2010–2014 and 2016–2017), was very similar to the abundance of sockeye salmon smolts migrated from Kurilskoe Lake for same period (Fig. 8a). The correlation coefficients \( r \) between these two indicators is 0.86. In this case, the difference between the numbers (averaged for all years of the observations) was only 0.525 million fishes, which is within an error corridor for the total generation abundance assessment, provided by different methods (Fig. 8b).

The presented data can confirm the conclusion about the high survival of Ozernovskaya sockeye salmon (or low interannual variability of this indicator) during downstream migration and early marine foraging; one of the most critical periods in the life cycle of Pacific salmon. In our opinion, this feature of the biology of Ozernovskaya sockeye salmon supports the high accuracy of the forecasted adult fish returns in the Ozernaya River in the last decade, when one of the basic sources for this forecast has become the estimation of smolt abundance as they migrate from Kurilskoe Lake. Thus, the average accuracy of the forecast of the returns of Ozernovskaya sockeye salmon (expressed as the ratio between forecasted abundance of the returns and the in-fact returns into the Ozernaya River basin) for recent 10 years was 103.6%.

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An Introduction to Canada’s New State of the Salmon Program

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Keywords: salmon, productivity, abundance, trends, forecasts, Pacific, status

Fisheries and Oceans Canada (DFO) has recently initiated a State of the Salmon (SOS) Program within its Pacific Region. The goal of this new program is to improve our shared understanding of the state of Pacific salmon populations, and the factors that contribute to their state, both within and outside of DFO. Fostering collaboration among scientific experts on salmon and their ecosystems is a key feature of this emerging program, and is necessary to accomplish its goals. Trends in abundance, productivity, and other biological characteristics of Pacific Salmon, such as fecundity, size-at-age, and run timing, will be tracked and compared across populations. Information on salmon will be linked to more detailed stock assessment monitoring, trends in the freshwater and marine ecosystems they occupy, and broader scientific research conducted on these populations and their ecosystems.

Fraser Sockeye have been used as a case study to build an initial framework for the SOS Program. Since this group of salmon is data rich, they have been monitored and studied extensively. Fraser Sockeye was the first group of Pacific salmon to undergo status assessments under Canada’s Wild Salmon Policy (WSP) (Grant et al. 2011; Grant and Pestal 2012). Populations are tracked annually through the preparation of pre-season return forecasts (Grant et al. 2010; MacDonald and Grant 2012; Fisheries and Oceans Canada (DFO) 2017, 2018). Additionally, considerable research has been conducted on Fraser Sockeye populations in their marine and freshwater ecosystems (Tucker et al. 2009; Beamish et al. 2012; Peterman and Dorner 2012; Preikshot et al. 2012; Irvine and Akenhead 2013; Ruggerone and Connors 2015; Freshwater et al. 2017a; Freshwater et al. 2017b).

There are currently 24 Fraser Sockeye conservations units (CUs) (Grant et al. 2011). Biological statuses for each of these CUs have been assessed using methods developed for the WSP. Under the WSP, a conservation unit (CU) has been identified as the fundamental unit of Canadian Pacific salmon biodiversity, based on salmon life-history, genetics, and ecological traits (Holtby and Ciruna 2007). Approaches used to identify WSP status for CUs provide not only an assessment of biological status but also a systematic method for tracking and communicating trends in salmon abundance and productivity (recruits-per-spawner). Overall, the Fraser Sockeye aggregate has exhibited declines in total returns and productivity throughout the last decade (Fig. 1). However, underlying the Fraser Sockeye aggregate is considerable biodiversity, and variation in abundance and productivity trends and biological status. WSP statuses vary across Fraser Sockeye CUs from Red (poor status), to Amber (moderate status), to Green (good status). Nine of these CUs have been recently assessed as Red or Red/Amber status zones (DFO 2018; Fig. 2).
There are 19 Fraser Sockeye CUs that are relatively data rich, with stock-recruitment data extending back to the 1950’s, depending on the CU (Grant et al. 2010, 2011). Comparisons of Fraser Sockeye CU productivity (recruits-per-spawner) have been conducted to identify periods of common and divergent patterns across CUs and time (Grant et al. 2010; Peterman and Dormer 2012). These comparisons can be used to identify drivers of these patterns at, respectively, broad regional or local scales. Specifically, differences in productivity trends between CUs can uncover unique aspects of their adult upstream migration, spawning and egg incubation, juvenile lake rearing, juvenile downstream migration, and/or ocean distribution that contribute to this variation.

Productivity for Fraser Sockeye CUs has been generally poor over the last decade, spanning the 2000 to 2013 brood years, corresponding to the 2003 to 2017 return years (Fig. 3). In particular, the 2005 and 2013 brood years (2009 and 2017 returns) of Fraser Sockeye exhibited extremely poor productivity across almost all CUs, producing two of the lowest returns on record for the Fraser Sockeye aggregate (Fig. 1). Declining productivity and returns leading up to the 2005 brood year (2009 return year), precipitated a legal inquiry into the cause of the declines, which was referred to as the Cohen Inquiry. There is some evidence that marine conditions in the Strait of Georgia, where all Fraser Sockeye CUs rear for a small portion of their life-history, contributed to synchronously poor productivity across most CUs specifically in the 2005 brood year (2009 return year) (Beamish et al. 2012).

However, the Cohen Inquiry concluded that no single ecosystem or factor was responsible for the declining trend...
Poor productivity in the 2013 brood year (2017 return year), occurred during a period of notably warm conditions in both freshwater and marine ecosystems (D. Patterson, DFO, David.Patterson@dfo-mpo.gc.ca, personal communication; I. Perry, DFO, Ian.Perry@dfo-mpo.gc.ca, personal communication; Chandler et al. 2016). DFO Science annually integrates research and monitoring across life-history stages and ecosystems to inform survival conditions for the upcoming Fraser Sockeye return year. For the 2017 returns, this integrative process noted warmer conditions throughout the life-history of Fraser Sockeye. This was particularly notable during the summer months of their adult upstream migration and also during their marine rearing stage. As these warm conditions were developing, Fraser Sockeye CU’s increasingly converged towards poor productivity, affecting the 2011 and 2012 brood years. Most recently, the 2013 brood year exhibited particularly poor productivity across all stocks, the synchrony and magnitude of which looked very similar to the 2005 brood year. However, the poor productivity of the 2013 brood year was likely linked to warm conditions throughout their life-history, as opposed to being isolated in the marine rearing stage, as in the 2005 brood year.

Although most CUs exhibited declining productivity trends from the 2000 to 2005 brood years, there are a few key exceptions. The Harrison river-type CU improved in productivity during this period (Grant et al. 2011). This CU has a unique life-history, ecology, and age composition compared to other Fraser Sockeye CUs (Grant et al. 2011). Harrison river-type salmon do not rear in freshwater lakes as juveniles prior to their migration to the ocean. Instead, these sockeye migrate to the ocean shortly after they emerge from their spawning gravel, and have a unique ocean distribution, spending more time in the Strait of Georgia than other Fraser Sockeye CUs (Beamish et al. 2016). Harrison river-type sockeye also return as three- and four-year-old fish, in roughly equal proportions (Grant et al. 2011), whereas most other CUs largely return predominantly as four-year-old fish. Though the exact factors contributing to the divergent patterns exhibited by Harrison Sockeye during 2000–2005 are unknown, their unique ecology and life-history likely contribute.

Another key exception to the declining productivity trend includes the populations that spawn and rear in the Shuswap Lake complex. These CUs have exhibited variable productivity that has oscillated around their long-term average in the past decade. Although their life-history is very similar to other Fraser Sockeye CUs, there is evidence that the density of juveniles in the Shuswap Lake complex in any year influences the productivity of subsequent cohorts (D. Selbie, DFO, Daniel.Selbie@dfo-mpo.gc.ca, personal communication; Levy and Wood 1992; Grant et al. 2011). Productivity for most fish populations is influenced by the density of adult spawners, or their cohorts, only in a single year (Ricker 1954). Therefore, although these CUs largely exhibit a similar life-history, age-at-return, and ocean distribution to other CUs, delayed-density dependent factors may contribute to the unique productivity patterns experienced by Shuswap Lake CUs.

From the 2006 to 2012 brood years, productivity patterns were mixed across CUs. This again suggests that there are localized factors influencing individual CU survival. Two CUs exhibited uniquely poor productivity in 2010 and 2011, and monitoring suggests that this can be attributed to factors occurring in their shared lake ecosystem (DFO 2014). Juvenile data for the Weaver CU (formally named Harrison (U/S)-L) shows average egg-to-fry survival in the 2011 brood year, however, juveniles from this CU were not detected in a smolt sampling program, located downstream of Harrison Lake, where these juveniles rear (DFO 2015). Therefore, a lake factor likely contributed to their observed poor survival. Birkenhead Sockeye (Lillooet-Harrison CU) also exhibited extremely poor productivity during this period, and coincidentally rears in Lillooet Lake, located a short distance upstream of Harrison Lake. Concurrently, a major landslide at the top end of this connected lake system dumped a large amount of sediments into the Lillooet River and subsequently Lillooet, and Harrison Lakes in August 2010. This increased turbidity in the Lillooet-Harrison lake system for a number of years. Empirical linkages between increased turbidity and poor productivity of these Sockeye CUs cannot be confirmed, however, since limnological and fry monitoring did not directly occur in these lakes.

Work on status evaluation, and tracking and comparing trends, such as that performed for Fraser Sockeye, has started to expand to other populations and species. Canadian WSP statuses have been assessed for Fraser River Coho (DFO 2015) and Southern B.C. Chinook (DFO 2016) salmon. Methods developed for Fraser Sockeye to compare and understand productivity trends (Peterman and Dorner 2012) have been extended to pink, Chinook, and chum salmon (Malick and Cox 2016; Malick et al. 2017; Dorner et al. 2018). The State of the Salmon Program will further consolidate and integrate this type of work across salmon populations in the Pacific Region through collaborative effort. This program recently hosted a Pacific Region State of the Salmon meeting to initiate integration and collaboration among scientists in the Pacific Region. It is also developing analytical approaches to improve our ability to explore trends. As this program evolves, these comparisons can be used in dialogue with...
local and regional experts on salmon and their ecosystems. Through initiatives like the International Year of the Salmon (IYS), this program will connect with salmon and ecosystem experts working globally on salmonid populations to better understand the global state of salmon and factors that influence them. The key to this program will be to develop integrative processes to synergize our collective knowledge.

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Environmental Factors Affecting the Survival of Juveniles and Recent Returns of Chum Salmon in the Okhotsk Coast of Hokkaido

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Keywords: chum salmon, Hokkaido, Okhotsk Sea, warm current

The Okhotsk coast of Hokkaido is the principal area of chum salmon, Oncorhynchus keta, production in Japan. In recent years, returns of chum salmon to the Okhotsk coast have been reaching historic highs, although decreases of chum salmon on the other coasts of Hokkaido have been remarkable since 2008 (Miyakoshi et al. 2013). The early marine phase is considered the critical period for the survival of chum salmon, that determines the subsequent number of fish returned. One of the likely causes for the regional difference in return rates is the recent changes in the coastal environment around the time that juvenile salmon migrate into the area (Nagata et al. 2016a). The recent high abundance of chum salmon in the Okhotsk coast should be due to the favorable ocean conditions and successful enhancement program. However, the returns of chum salmon to the Okhotsk coast of Hokkaido have decreased since 2014; with extreme low returns of the 2010, 2012, and 2013 brood year classes were observed.

In the coastal waters of Abashiri on the eastern Okhotsk coast of Hokkaido (Fig. 1), we have conducted a field survey since 2002 to monitor seawater temperature, salinity, zooplankton abundance, and density of juvenile chum salmon from late April to early July (Nagata et al. 2007). The coastal environmental conditions in the Okhotsk coast are affected by the warm oceanic current called the “Soya Warm Current”, which is defined by high salinity (> 33.6psu) (Asami et al. 2007). In this study, we examined the effects of such environmental factors on the survival of chum salmon on the eastern Okhotsk coast of Hokkaido.

When the effects of the environmental factors were examined, a significant relationship was observed between seawater temperature in May and number of chum salmon returned ($R^2 = 0.422, p < 0.05$), but there were no significant relationships for seawater temperature in June, or zooplankton abundance. Also, numbers of juvenile chum salmon captured in the coastal area by trawl survey and numbers of returns of the brood year were weakly
correlated ($R^2 = 0.420, p < 0.05$). This may indicate sea water temperature just after ocean entry may be an important factor affecting the survival of juvenile chum salmon. Zooplankton biomass in this region may be abundant enough for juvenile chum salmon even in the years of low abundance; as a result, yearly fluctuation of zooplankton biomass did not have a significant effect on the numbers of returning chum salmon in this region.

When the Soya Warm Current was weak (2011, 2014), the returns of chum salmon of the brood year classes tended to be low, although its effects were not significant. The flow of the Soya Warm Current is weak in winter and expands in spring and early summer. The expansion of the Soya Warm Current affected the seawater temperature, salinity, and abundance and composition of zooplankton in the coastal area where juvenile chum salmon distribute (Asami et al. 2007). These former studies indicated that the seawater temperature affects the return rates of chum salmon in this region (Miyakoshi et al. 2007; Nagata et al. 2016b). The timing of the expansion of the Soya Warm Current may relate to the distribution, the timing of offshore migration of juvenile chum salmon, and the subsequent survivals in the Okhotsk coast of Hokkaido.

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Interannual Dynamics of Abundance of Pink and Chum Salmon Juveniles and their Average Body Size in the Sea of Okhotsk in 1998–2017

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Keywords: juvenile pink salmon, juvenile chum salmon, abundance, body weight, plankton biomass, the Sea of Okhotsk

In the early 2000s, there were notable changes in the climate and oceanography in the Far Eastern seas, which were reflected in biotic changes (Shuntov 2016). A gradual decrease in the ice cover was observed in the Sea of Okhotsk (Ustinova and Sorokin 2013). From 2006–2017, the ice cover of the Sea of Okhotsk was minimal for the last 60 years (Fig.1).

A progressive decrease in plankton biomass was observed after 1980 in the Sea of Okhotsk, and it increased in the Bering Sea and adjacent Pacific waters during the same period (Shuntov and Temnykh 2011; Shuntov and Volvenko 2017) (Fig.2). In the nektonic communities, an increase of subtropical fish abundance has been observed in the Sea of Okhotsk since the second decade of the 2000s (Shuntov 2016). Along with changes in plankton and nekton communities in the Far Eastern seas, certain changes in the dynamics of salmon regional stock abundance have been noted. A negative trend of abundance dynamics was present in some southern salmon stocks in the second decade of the 2000s (Shuntov and Temnykh 2017). At the same time, the abundance of pink and chum has increased in the northern coastal areas, which was partly associated with favorable conditions for reproduction beginning from the first decade of the 2000s.

Research objectives of this investigation are to consider the features of the dynamics of abundance and average body weight of pink and chum salmon in the southern part of the Sea of Okhotsk during relatively “cold” (1998–2006) and "warm" (2007–2017) periods and to assess the impact of a decrease in plankton biomass in the Sea of Okhotsk on the abundance, size and mortality of juveniles.

This study is based on findings of 20 complex epipelagic surveys conducted in the Sea of Okhotsk by TINRO-Center in September–November 1998–2017. The surveys included abundance estimation of salmon, ecologically-related plankton and nekton species, and fish diet analysis. Fish were sampled with pelagic trawls (vertical opening 25–45 m, horizontal opening 35–50 m) equipped with a small-size mesh (1 cm) lining the cod end. Zooplankton samples were obtained using a Jedy net (0.1 m$^2$ mouth opening and 0.168-mm mesh). For more details see Shuntov (2001).

The abundance of pink salmon juveniles in the Sea of Okhotsk in 1998–2017 varied within the range of 442 million–1.833 billion fish for odd generations, and 569 million–1.507 billion fish—for even generations. In autumn 2017, the highest level of juvenile pink salmon abundance (2.752 billion fish) was recorded in the Sea of Okhotsk (Fig. 3). Pink salmon have absolutely dominated among salmon juveniles, ranging from 53 to 89% of their total abundance. Chum salmon juveniles’ abundance varied from 164 to 926 million individuals during the study period, an average of 32% of the total abundance of these two salmon species.
Fig. 2. Long-term dynamics of total zooplankton biomass (mg/m$^3$) in the epipelagic layer of the North Pacific (Shuntov and Volvenko 2017). Right inserts show interdecadal change of the biomass: red—decrease, green—increase.

The annual average body weight of the pink salmon juveniles was 154.2 g, varying within 107–198 g. The annual average body weight of the chum salmon juveniles was 145.1 g varying within 115–176 g (Fig. 3).

As shown in Fig. 3, the dynamics of both pink salmon and chum salmon abundance and their average sizes is synchronous. Statistically significant Spearman correlation coefficients between pink and chum juvenile salmon abundance and between average body weight of these species are very high (respectively $r = +0.84$ and $r = +0.83 (p<0.05)$) (Table 1). As it was noted earlier, (Shuntov and Temnykh 2008; Radchenko at al. 2013; Temnykh at al. 2017), these features of dynamics of the pink/chum abundance and their body size, as well as the features of spatial distribution (cohabitation during the autumn feeding migrations) indicate the complementarity of these species. Furthermore, the changes in abundance and average body size of pink and chum salmon juveniles in the western Bering Sea are similar (Fig.4), despite the fact that the East Kamchatka juvenile pink salmon are many times more abundant compared to the chum salmon. Statistically significant Spearman correlation coefficients between pink/chum juvenile salmon abundance and between average body weight sizes of these species are very high (respectively $r = +0.85$ and $r = +0.79 (p<0.05)$).
Fig. 3. Dynamics of abundance and average body size of pink and chum salmon juveniles in the Sea of Okhotsk in fall 1998–2017.

Table 1. Spearman Rank Order Correlations Coefficients between abundance and average body weight pink and chum salmon juveniles of Okhotsk sea stocks.

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<th>Juvenile chum salmon abundance</th>
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The higher abundance of both pink salmon and chum salmon was observed in the Sea of Okhotsk during the relatively colder period (1998–2006). This period was characterized by relatively higher concentrations of macroplankton in the southern part of the sea (in average 110 g/m²). In the subsequent warmer period of 2007–2016 (the period of minimum ice cover of the Sea of Okhotsk), a decrease in the macroplankton biomass was noted in the southern part of the sea (to an average of 64 g/m²). The number of salmon yearlings has also decreased (Fig. 3). Formally, a statistically significant positive correlation is observed between the concentrations of plankton and the number of salmon juveniles in the deep-water part of the Sea of Okhotsk. Spearman correlation coefficients between average macroplankton biomass and abundance of each species were +0.51 ($p < 0.05$). However, the food
supply of salmon juveniles is not a factor limiting salmon abundance in the southern part of the Sea of Okhotsk in the autumn of the 2000s.

- Despite the decrease in plankton concentrations in 2006–2016, their reserves in the deep-waters of the sea are very large. In the “warm” period, the plankton biomass per 1,000 juveniles has increased from 28.6 to 37.6 metric tons.

- More stringent food relationships among salmon yearlings due to density-dependent factor were characteristic for the cold years of 2000–2006. In the warm years of 2007–2011, conditions with high food supply for juveniles were observed (Zavolokin 2013; 2014).

- The plankton biomass decrease did not affect the change in the average size of the juveniles, as evidenced by the absence of statistically significant correlation between the average size of chum and pink juveniles and macroplankton biomass in the southern Okhotsk Sea. A significant decrease in the average size of pink salmon juveniles in even generations (an average of 20 g) is due to an increased abundance of Kamchatka stocks in the Sea of Okhotsk in the period 2007–2016. Kamchatka pink salmon juveniles are smaller in comparison with the pink salmon juveniles of the southern stocks. When Sakhalin-Kuril pink salmon stocks dominated in the Sea of Okhotsk, the average size of juveniles did not change and amounted to an average of 161 and 165 g, respectively for the periods of 1998–2006 and 2007–2016. In general, the average sizes of juvenile pink salmon depend on the proportion of “south” stocks in the sea of Okhotsk ($R = +0.72$ ($p>0.05$)).

Fig. 5. Survival rates of pink salmon belonging to the Sea of Okhotsk stocks during period from fall surveys until spawning approaches to coasts, 1998–2017.

Despite the lower abundance of pink salmon juveniles in the sea of Okhotsk during the last 10 years, their survival increased in the following marine life stages (Fig. 5). So, the survival rate of pink salmon for odd generations increased on average from 14 to 17% in comparison with the period of 1998–2006, for even generations almost twice as much (from 12 to 21%). An increase in survival rates of the juvenile pink salmon by half during winter and spring in 2008–2011 indicated the presence of favorable forage conditions in “warm” period. A noticeable increase in the survival rate of pink salmon in the last 10 years is due, first of all, to the lower death rates of the pink salmon from the “northern” stocks (Kamchatka and the continental coast of the Sea of Okhotsk).

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Present State and Future of Far East Salmon Stocks under Changing Climate
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Keywords: Far East salmon stock, long-term climate change, sea surface temperature anomalies, 60-year cycle, present state of salmon stocks

Introduction
Over the last 100 years, the Far East salmon stocks have been characterized by substantial long-term variability (Fig. 1). The period of their high abundance in the 1920s–1940s was followed by depression of the stocks in the 1960s and the 1970s. The new rise of abundance and biomass of Far East salmons began in the 1980s, and in 2009 the total Russian catch reached its maximum of 540,000 metric tons. The data for 1910–1971 in Fig. 1 was taken from Klyashtorin and Smirnov (1992). They took into account the Japanese catches in Russian waters. The catch statistics for 1972–2017 is available online from the NPAFC website (www.npafc.org). Mean monthly sea surface temperature (SST) values were taken from the ERSST v3b dataset, available online at http://www.esrl.noaa.gov/psd (Smith et al. 2008).

Fig. 1. Dynamics of total Far East salmon catch in 1911–2015. Vertical lines show periods of growth and high level of the salmon stocks.

Fig. 2. Trend component of mean annual SSTA in the North Pacific (1911–2015) corresponding to EOF2 PC (14%) of the anomaly field. Vertical lines show periods of sharp increase in SST.

Long-term changes in the Far East salmon stocks
The periods of growth and high levels of Far East salmon stocks in 1916–1945 and 1982–2013 coincided with a tendency toward a sharp increase in SST in the North Pacific (Fig. 2). This Figure demonstrates the trend component of mean annual SST in the North Pacific from 20°N to 65°N and corresponds to EOF2 PC of the SST anomaly field, explaining 14% of its total variance. It should be noted, however, that climatic reasons of the sharp increase in surface temperature for these two periods were different.

Fig. 3. Correlation patterns between total Far East salmon catches and mean winter (I–IV) SSTA in the North Pacific for periods 1916–1945 (a) and 1982–2013 (b).
Fig. 3 shows the correlation patterns between the total catches of Far East salmons and mean winter (I-IV) SST anomalies (SSTA) in the North Pacific for two periods of high salmon production—1916–1945 and 1982–2013. As seen in Fig. 3a, the growth of salmon stocks in 1916–1945 was associated with surface warming in the eastern ocean which spread westward along the Aleutian Islands to the Kamchatka coast and the eastern Sea of Okhotsk, thus covering all habitat areas of salmons during their marine period of life. The warming in the eastern North Pacific is a characteristic feature of the positive Pacific Decadal Oscillation (PDO) phase. In fact, this period was characterized by the development of the positive PDO phase, with its establishment in the early 1920s and ending in 1945.

In contrast, the second period of growth of the Far East salmon stocks (1982–2013) coincided with a sharp warming in the western and central ocean (Fig. 3b). This warming was a result of the establishment of a new climatic regime in the North Pacific in the late 1980s that was accompanied by the shift of a “center of gravity” of climatic variability from the eastern ocean to its western part. This warming was related to the developmental character of upstream climatic processes in the Atlantic—Eurasian sector of the Northern Hemisphere.

![1916-1945 and 1982-2013 SST anomalies](image)

Fig. 4. Linear trend values (°C/year) of mean annual SST in the North Pacific for periods with high Far East salmon stock state.

The obtained results are confirmed by the distribution of linear trend values of mean annual SST in the North Pacific for two periods under consideration (Fig. 4). The comparison of the main spatial features in Fig. 3 and Fig. 4 shows their great similarity. Thus, both periods of increase in the Far East salmon stocks over the last 100 years were closely related to the pronounced strengthening of the tendency toward warming of surface waters in the North Pacific. However, the climatic mechanisms of the warming, and correspondingly, areas of its maximum manifestation were different.

![Difference of SSTA in May–June between 1946–1981 and 1916–1945](image)

Fig. 5. Difference of SSTA in May–June between 1946–1981 and 1916–1945.
The relationship of Far East salmons during the period of decrease in their stocks (1946–1981) with SSTA is not so simple. First of all, it should be noted that after a peak in 1945, the mean level of temperature anomaly variations associated with PC2 (trend component) lowered but remained positive over most of the period from 1946 to 1981, being indicative of continuing warming, though not so intensive. The weak negative values of PC2 were noted only in the second half of the 1970s. As seen from Fig. 5, the period of 1946–1981 was even warmer as a whole than the 1916–1945 period. Thus, it may be supposed that growth of the Far East salmon stocks both in the first half of the 20th century and in the late 1980s was not associated with the absolute values of SST but with strong warming trends.

![Fig. 6. The North Pacific SSTA and salmon periods: SSTA in the NP (0-65°N, 110–260°E) smoothed by 121-month filter (a); detrended SSTA with salmon periods, including projection of next growth of Far East salmon stock (b).](image)

When analyzing the North Pacific SSTA with the pronounced warming trend, it is clearly seen that during some multidecadal periods, the anomalies are above the trend line, and they are below the trend line during other multidecadal periods (Fig. 6a). These multidecadal variations have a period of roughly 60 years but warming and cooling periods vary in length and magnitude. The warmer and colder phases of a multi-decadal cycle are expressed much better after removing the linear trend (Fig. 6b). It is not surprising that periods of high salmon abundance in the 20th and early 21st centuries began on ascending branches of multi-decadal cycles and continued till they reach their maxima. Continuing the 60-year cycle into the future allows us to project the beginning of the next salmon period around 2040.

**Recent climatic variations in the North Pacific**

However, one question still remains—whether the present salmon period has already ended or not. The climatic regime established in the North Pacific in the late 1980s favored the growth of the Far East salmon stocks. This situation continued till 2011. Yet in 2007–2011 the distribution of mean winter SSTA in the North Pacific corresponded well to the correlation pattern between salmon catches and winter SST anomalies (Figs. 7a, b).

However, the characteristic feature of a thermal regime in the Northwest Pacific during the next two years (2012–2013) was associated with the development of negative SSTA over the vast aquatory which covered the eastern Okhotsk Sea and areas east of Kamchatka. (Fig. 7c). The negative temperature anomalies remained not only until the end of spring season but sometimes they continued through the first two ten-day periods of June. The following summer months were characterized by intensive seasonal surface warming with positive SST exceeded 3–4°C (Fig. 7d). These intra-annual changes in the thermal regime created the unfavorable conditions both for survival and development of salmon juveniles at their early marine life stage and for adult fish approaching the coastal zone for spawning.

The sharp warming of surface waters in the Northeast Pacific (the Blob) in January 2014, started to affect the Bering Sea aquatory in spring and resulted in substantial increase in SST in the eastern Sea of Okhotsk and Kuril Islands area in late summer 2014 (Fig. 8).

In the late spring—early summer of 2015–2016 the thermal conditions in the Bering Sea did not differ essentially from the conditions in 2014 and were determined by anomalous surface warming in the Northeast Pacific. This warming was augmented by strong El Nino event of 2015–2016. This created favorable conditions for the development of juveniles of East Kamchatka pink, chum, and sockeye salmons.
Fig. 7. Some features of temperature field in the North Pacific in 2007–2013.

Fig. 8. SSTA patterns in the North Pacific in January–April (a), May (b) and July–October (c), 2014.

Conclusion

1. As a whole, during the last 10 years, there were very considerable variations in catch volumes of main Far East pink salmon stocks. After the peak catch of East Kamchatka stock of 182,000 metric tons in 2011 and West Kamchatka stock of 165,000 metric tons in 2012, their catches decreased substantially, respectively to 37,000 metric tons in 2013 and 8,200 metric tons in 2014. In 2015, the East Kamchatka pink salmon catch rose again more than two times, up to 89,000 metric tons, and the catch of West Kamchatka pink salmon in 2016 increased nine times.
Moreover, in 2016 there was a sharp increase in catch of even-year generation of East Kamchatka pink salmon. During 2011–2015 there was a 4-fold decrease in odd-year generations of pink salmon off the East Sakhalin.

2. These wide variations in pink salmon catches, and in a broader context, in their stocks were associated with the above-mentioned changes in climatic conditions, which reflected the intensifying short-term variability in the NP climate. It may be supposed that the occurrence of short-term “heat” and “cold” waves will increase during the next decades. This will make difficult to project the state and catches of Far East salmons.

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Validity of Inferring Size-selective Mortality in Pacific Salmon from Scale Circulus Spacing

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Keywords: critical size limit, critical period, Pacific salmon, size-selective mortality, scale circulus spacing

Beamish and Mahnken (2001) proposed that most natural mortality of Pacific salmon during the marine life history phase was size-dependent and occurs in two major episodes. The first phase of mortality was suggested to be predation based and occurs after the smolts enter the ocean, with other studies on salmonids typically reporting relatively high mortality after initial ocean entry (Parker 1968, Hartt 1980). The second phase of mortality was suggested to occur in the fall and winter of the first year in the ocean, when those individuals that have not attained a critical size die because they are unable to meet minimum metabolic requirements (Beamish and Mahnken 2001). Beamish et al. (2004) indicated that Pacific salmon had to achieve a sufficient size by the end of the first marine summer to be able to survive the metabolic demands during a period of energy deficit in the late fall and winter.

If evaluation of differences in frequency distributions of individuals with different scale circulus spacing is a valid way to infer size-selective mortality of juveniles, then a number of predictions can be made with respect to the distribution of individuals with different circulus spacing within the population. First, there should be a positive correlation between circulus spacing and body size both within and among sampling periods, as individuals with wider circulus spacing are imputed to be faster growing and thus larger. Next, if circulus spacing is a permanent record of growth, there should be a wide range of circulus spacing within the population of juveniles sampled during the first marine summer, but during the late fall and winter as hypothesized size-selective mortality occurs, individuals with narrow circulus spacing should disappear from the population as they were unable to attain the critical size necessary for survival during the first winter of ocean residence. There should be little identification of individuals later in the life cycle with circulus spacing unobserved during the first summer of rearing, merely a change in the relative frequencies of circulus spacing observed in the juvenile population during the first summer of rearing. Therefore, one should expect that the range of circulus spacing in the population should be greater during the first summer of marine rearing than later in the life cycle, and that the variance in circulus spacing within the population should be greater in the first summer than later in the life cycle.

Under the assumption that size-selective mortality would operate on the smaller members of the juvenile population, we investigated the expected distribution of the scale circulus index and the associated descriptive statistics of the distribution under expectations that failure to achieve a critical minimum would remove up to 80% of the existing population. As the projected juvenile mortality rate increased, the mean of the scale index of the remaining (adult) population increased, the range of the scale index declined, as did the standard deviation of the index. The skewness of the distribution of the index values of the remaining individuals increased positively, with higher values observed under more extensive mortality scenarios.

If size-selective mortality is operating on the smaller individuals in the juvenile population, then one should observe a shift in the frequency distribution of the scale index towards values associated with larger individuals. It is expected then that the scale circulus index of the adults should fall within the range of the index observed for the juveniles, but as juveniles with smaller values of the index are selectively removed from the population, then the range of the index observed in the adult population should be less than observed in the juveniles, and thus variance will be lower. There should also be higher positive values of skewness of the distribution in the adult population compared with the juvenile population.

Bond et al. (2008) compared the size distributions of hatchery-reared steelhead (O. mykiss) smolts sampled immediately before release with the back-calculated size at ocean entry of surviving adults from the same cohort. All adults in the sample displayed back-calculated fork lengths that were observed in the smolts upon release, and the back-calculated lengths were a subset of those observed in the smolts, with a shift in the frequency distribution of size towards values associated with larger individuals. These results illustrate what would be expected if the smaller individuals in the smolt population experienced size-selective mortality. We suggest that the key here was
that the juvenile samples were representative of the entire population, as the juveniles were sampled before hatchery release, and the returning adults must necessarily have been derived from the sampled juvenile population.

Some studies occur where the juvenile sample was obtained not from a hatchery prior to release of the juveniles, but instead was obtained by sampling juveniles after they had been rearing for a period of time in the ocean. Beamish et al. (2004) measured mean intercirculus spacing of the first 10 marine circuli of coho salmon in the Strait of Georgia in British Columbia, with juveniles sampled in September and November of their first year of ocean rearing (marine age 0). The results display the opposite results to those expected under a size-selective mortality environment directed at the smaller members of the population. The range and variance of the scale index values of the marine age-1 individuals were actually larger than those of the age-0 individuals, and skewness of the distribution actually declined, indicative of relatively more marine age-1 individuals with narrow circulus width spacing than would be expected.

Moss et al. (2005) measured distances from the scale focus to specific circulus for three hatchery populations of pink salmon in Prince William Sound, Alaska. Size-selective mortality was inferred by comparing the frequency and means of scale radius length classes at specific circulus for juveniles from the hatcheries sampled in July, August, and September in the year of release with that of adults that returned to the three hatcheries the following year. If substantial size-selective mortality were present between the juvenile and adult life history stages, then most adults in the sample should display circulus width values observed in the juvenile population, and the range and variance of the adult circulus spacing values should decline. It seems likely that the juveniles sampled were not representative of the whole population and underestimated the presence of the larger pink salmon that were resident in the ocean but unavailable to the summer and fall sampling regime, resulting in an overestimation of the impact of size-selective mortality on the populations.

A fundamental question to answer is how it is possible that adults derived from a juvenile population displayed values greater than the maximum observed in the juvenile population. One possible explanation is that the larger-sized individuals in the juvenile population were not available to be sampled when the initial distribution of the scale circulus values in the juvenile population was determined. The larger-sized individuals could have selectively moved from the geographic sampling area (Beacham et al. 2014, 2016, 2017), or they could have moved deeper in the water column making them unavailable to the sampling gear. It is possible that larger-sized juveniles were not available to be sampled as juveniles, but were available to be sampled as adults, resulting in observed scale circulus values outside of the range observed in juveniles. As outlined by Beacham et al. (2017), movement of larger-sized juvenile coho salmon likely from the Strait of Georgia did occur prior to the collection of first ocean year individuals by Beamish et al. (2004), and thus there was little support for the hypothesis that coho salmon experienced size-selective mortality and had to achieve a sufficient size (the “critical” size) by the end of the first marine summer or fall to be able to survive during the winter of their first year of ocean rearing.

Size-selective mortality is often invoked as an important driver of population dynamics of Pacific salmon (Beamish et al. 2004), so much so that the concept has been introduced of the necessity of obtaining a “critical size” by the fall of the first year of ocean rearing in order to ensure survival over the winter (Beamish and Mahnken 2001), a potential second “critical period” (Howard et al. 2016). There is no doubt that there can be substantial mortality of Pacific salmon during their first year of ocean residence. However, in order to invoke size selection as an important driver of this mortality, we suggest that it is necessary to demonstrate that size-selective mortality directed towards the smaller members of the population can account for a substantial portion of the observed mortality. With respect to size, a critical size implies that the individuals must attain this size or die; for a size to be defined as “critical,” it must be demonstrated that the proportion of the population failing to attain this size by the specified period can account for the observed mortality. Studies that employ scale characteristics to infer size-selective mortality need to show that all scale index classes in the adult population were indeed present in the juvenile population, and that the adult scale classes were a subset of those present in the juvenile population.

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Keywords: Critical size, Pacific salmon, winter, size selective mortality

For Pacific salmon, their early marine residence and first winter at sea are hypothesized as “Critical Periods” where mortality within a cohort can be large. Sogard (1997) suggests that mortality acts on a cohort in three possible ways: 1) indiscriminately—there is the same probability of mortality for all individuals (i.e., larval life history stage); 2) randomly—mortality is inconsistent or unpredictable; and 3) non-random—traits within a cohort reduce “relative” risk of mortality. For juvenile salmon, mortality is hypothesized to be “non-random” where the traits used to define “critical periods” include size and lipid storage that juveniles attain during their first summer at sea. These traits are a reflection of the marine ecosystems that the juvenile salmon experience. This concept of a critical period (summer growth and energy storage) has also recently been developed for young of the year pollock and Pacific cod within the Bering Sea (Hunt et al. 2011; Coyle et al. 2011; Heintz et al. 2013; Farley et al. 2015).

Beacham et al. (2018) assume size-selective mortality is a “knife-edge” process, where fish that do not reach an “absolute” critical size die. They simulated two size frequencies under this assumption and then compared statistics from the simulated size frequencies to previous work that used empirical data. In natural marine systems, fish do not exhibit a knife-edge mortality. Instead, there is a decreasing probability of size-related mortality as fish become larger. For example, Howard et al. (2016) illustrate (Fig. 1) the probability of size-selective mortality in relation to juvenile Yukon River Chinook Salmon weight. Weight is a proxy to energy density (lipid), which is a key biological trait when assessing the health of a population prior to their first winter at sea. Fish scale to fish length, fish length to fish weight, and fish weight to fish energy density relationships are all described via statistical relationship with error distributions. Thus, even if there was a single critical energy density value (i.e., a knife edge mortality) instead of a range of weights (energy densities) as demonstrated by Howard et al. (2016), we would still expect to see a broader distribution of scale circuli and fish lengths associated with these densities, rather than a knife edge mortality as suggested by Beacham et al. (this volume).

![Fig. 1.](https://example.com/fig1.png)

**Fig. 1.** (Fig. 7 from Howard et al. 2016) Generalized additive model (thick solid black line) fit to size selective mortality (SSM) probabilities of juvenile Yukon River Chinook Salmon based on differences between actual juvenile weights and the average of simulated back-calculated weights of adults during the second critical period (summer growth prior to the first winter at sea). The horizontal dashed 0.5 probability line identifies the reference point of neutral selection of the GAM model; a selective disadvantage is expected for weights smaller than this point, a selective advantage is expected for weights larger than this point. Shaded area represents GAM model confidence intervals.
Fig. 2. (Fig. 3 from Farley et al. 2011) Scatterplot displaying the relationship between energy density (ED; kJ g⁻¹ wet weight) and fork length (mm) for juvenile sockeye salmon collected during autumn 2003–2008 in the eastern Bering Sea. Linear lines for each year were fit to the data to illustrate differences in the relationship between ED and fork length for juvenile salmon among years.

Fig. 3. (based on Fig. 5 from Farley et al. 2011) The relationship between the natural log of fork length and lipid for juvenile (squares), ocean age-1 (diamonds), and ocean age-2 plus (triangles) collected during autumn 2008 (juveniles) in the eastern Bering Sea and winter 2009 (age-1 and age 2+) in the North Pacific Ocean.
Fig. 4. (Fig. 6 from Farley et al. 2011) The relationship between the marine survival index (MSI) and energy density (ED; kJ g⁻¹ wet weight) for juvenile salmon caught during autumn of 2003–2007 in the eastern Bering Sea.

The role of juvenile salmon size and mortality is dynamic and complex: ecosystem processes like temperature regime, ontogenetic timing, prey dynamics and predator dynamics are expected to interact with size-selective mortality processes in a variety of ways, at multiple time scales and at different magnitudes. Farley et al. (2011) found that energy (lipid) is related to the length of fishes; however, this relationship can vary (in both intercept and slope) depending on ecosystem dynamics during summer months. Sometimes a smaller fish can have more lipid during one year than a fish of similar size during other years (Fig. 2 from Farley et al. 2011) and the path to high or low lipid states during summer for fish is likely a function of temperature and prey quality and quantity. Therefore, size-dependent mortality can vary depending on quality and quantity of prey, suggesting that critical-size (as it relates to energy reserves) can also vary. Farley et al. (2011) also note that the relationship between energy and size shifts during the first winter at sea for juvenile to age-1 Bristol Bay sockeye salmon (Fig. 3). The seasonal signatures for lipid and protein suggest that ocean age-1 sockeye salmon are not starving, but instead the larger fish are likely utilizing energy stores to minimize predation. Energy density that juvenile sockeye salmon accumulate during summer is also strongly related to their marine survival (Fig. 4).

The time frame defining a critical period when size-selective mortality may be most influential should also be expected to be dynamic, complex, and stock-specific. Farley et al. (2007) used survey data to estimate the abundance of juvenile Prince William Sound (PWS) hatchery pink salmon during August. They then compared this estimate to the number of PWS hatchery pink salmon released and the number of PWS hatchery adult pink salmon that returned the following year. They found that the highest marine mortality occurred prior to the August survey (93%), but there was still substantial marine mortality after the survey (26%) illustrating the magnitude of mortality during the two critical periods (first 40 days at sea and winter) for juvenile pink salmon. Moss et al. (2005) found that surviving adults were significantly larger than juveniles at the same circulus for 5 different circuli comparisons using scales collected from juvenile and adult PWS hatchery pink salmon. These size frequency comparisons provide evidence that juvenile pink salmon undergo significant size-selective mortality after the first growing season. Beacham et al. (2018) focused only on circuli 15 (Fig. 5) and suggest that the distribution patterns between juveniles and adults for this circuli comparison do not conform to their hypothesis regarding size-selective mortality. They suggest that Moss et al. (2005) likely missed the larger cohorts in the populations of hatchery pink salmon, thereby overstating the significance of selective processes over winter. While this is a possibility, it is also a possibility that a restricted approach to defining the timing of a critical period may underestimate natural processes. It is also highly likely that the survey missed the smaller cohorts within the population, thereby understating the significance of selective processes over winter.
**Fig. 5.** (Fig. 2 from Moss et al. 2005) Relative frequencies of scale radius length to circuli 3, 6, 9, 12, and 15 for hatchery pink salmon juveniles (dotted lines) and individuals of that cohort returning the following year as mature adults (solid lines) released by Armin F. Koernig (AFK), Cannery Creek (CC), and Wally Noerenberg (WN) hatcheries in 2001 (brood year 2000).

**Conclusion**

Beacham et al. (2018) assume mortality for fishes within natural populations is a knife edge function. Their illustration is one that is unlikely to occur in nature and is inconsistent with the descriptions of size-selective mortality in the literature they cite. The critical-size literature cited attempts to describe the increased likelihood of survival for those individuals that meet the energetic needs for over-winter survival and a size that reduces predation risk. Therefore, their interpretation of size-selection based on skewness and kurtosis for a population experiencing “knife edge” mortality is not a valid comparison to our empirical data distributions.

Simulations can be used to support alternative hypotheses for many ecological studies. However, several assumptions used in the Beacham et al. (this volume) simulations lead to an over-simplified attempt to undermine the conclusions drawn from empirical data. The empirical data allows for the inter-play between size and energy density, and they allow for inter-annual variability in the natural environment. Such biological and environmental stochasticity is ignored in the simulations.
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Pink Salmon as Sentinels for Climate Change in the Arctic

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Keywords: Arctic, Pacific salmon, distribution

The Pacific Arctic Region (PAR), that includes the northern Bering Sea (NBS), across the Chukchi Sea to the East Siberian and Beaufort seas, is experiencing significant warming and extremes in seasonal sea ice extent and thickness (Frey et al. 2014). Over the past decade, record summer sea ice minima (2007, 2011, 2012) have occurred and climate models predict that the southern Chukchi Sea will be sea ice free for five months (July to November) within a decade or two (Overland et al. 2014). These shifts to the PAR ecosystem are likely to have large impacts on the ecology of upper trophic level species (UTL, fishes, birds, and mammals; see Sigler et al. 2011). Because the UTL are typically top predators, they must adapt via biological responses to physical forcing and thereby become “sentinels” to ecosystem variability and reorganization (Moore et al. 2014). As such, there will likely be fishes that do better under climate warming and those that may not.

Fig. 1. Biomass (metric tonnes) of juvenile pink salmon captured in the northeastern Bering Sea during 2002 to 2017; there was no survey during 2008.

Pacific salmon have a historic presence in the Arctic but have typically occurred in low numbers (Craig and Haldorson 1986; Bockstoce 1988; Nielson et al. 2013). More recent information, however, indicates that Pacific salmon have become more prevalent in subsistence catches in the Arctic (Beaufort Sea region) (Dunmall et al. 2013; Carothers et al. 2013; Stephenson 2006; Dunmall et al. 2018). Using a community-based monitoring approach to assess trends in salmon presence across the Canadian Arctic, both reported abundances and the geographic distribution of occurrences are generally increasing (Dunmall et al. 2013; Dunmall et al. 2018). Subsistence harvests of pink salmon, specifically, have increased in even-numbered years since 2004 (Dunmall et al. 2013; Dunmall et al. 2018). As there are no self-sustaining populations of pink salmon suspected in the Canadian Arctic at this time, the source populations for these vagrants are currently unknown.
Fig. 2. The relationship between juvenile pink salmon biomass (metric tonnes) captured in the northeastern Bering Sea and subsequent (one year later) adult returns of pink salmon as indexed at Pilot Station on the Yukon River.

\[ y = 249.74x + 3238.8 \]
\[ R^2 = 0.6378 \]

0 200,000 400,000 600,000 800,000 1,000,000 1,200,000 1,400,000 1,600,000

0 1000 2000 3000 4000 5000

Fig. 3a–d. Juvenile pink salmon catch per unit effort (CPUE) within the Chukchi Sea during August to September 2007 (a), 2012 (b), 2013 (c), and 2017 (d). The “x” indicates stations where fish sampling occurred by no juvenile pink salmon were captured; the exception is 2017 where sampling for juvenile salmon occurred only within the nearshore (two sampling stations nearshore; no samples taken further offshore).
A juvenile pink salmon abundance index (Fig. 1) that is obtained from annual integrated ecosystem surveys conducted in the NBS (see Murphy et al. 2017 for details on the survey) is related to adult pink salmon returns the following year to the Yukon River (Fig. 2). The result suggests that pink salmon production is increasing within the NBS region. However, the juvenile pink salmon index obtained from similar surveys in the Chukchi Sea illustrates that catches can be high, such as during 2007 (Fig. 3a), but have typically been very low as seen during 2012, 2013, and 2017 surveys (Fig. 3b–d). The large catch of juvenile pink salmon during 2007 coincided with higher adult returns to the Beaufort Sea coast in 2008 (Dunmall et al. 2013; Dunmall et al. 2018); but it is unclear if these juveniles were the product of successful spawning in the Arctic. Nevertheless, these overall changes may be indicative of a changing PAR marine environment, suggesting that Pink salmon could be a potential candidate as a “sentinel” species for Arctic change (Dunmall et al. 2013).

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Understanding the Mechanisms that Regulate Coho Salmon Abundance in the Strait of Georgia, British Columbia, Canada

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Canada

Keywords: Coho salmon, migration, Strait of Georgia, metabolic threshold

There was an important commercial and recreational fishery for coho salmon in the Strait of Georgia, British Columbia, Canada in the 1970s and 1980s. The recreational fishery was one of the largest in Canada with average annual catches of 508,000 fish from 1980 to 1990 (Beamish et al. 1999). However, in the late 1980s, it was evident that abundances were declining (DFO 1990, 1992; Irvine et al. 1992). The declines continued into the 1990s with the closure of the commercial fishery in 1995 and the recreational catches diminishing to very low levels after 1994 (Beamish et al. 2008). The declines in abundance were related to the loss of freshwater habitat and to an exploitation rate that was too high (DFO 1990, 1992).

However, the synchronous declines in abundance for coho salmon from the Strait of Georgia, Puget Sound and off the coasts of Washington and Oregon (Beamish et al. 2000) indicated that the major reason for the declines resulted from a declining marine survival that was related to a change in the ocean ecosystem. Importantly, the abundance declines in all these areas occurred despite additions of smolts from hatcheries that annually averaged about 100 million fish (Beamish et al. 1997), clearly showing that the declines were mainly a result of changing ocean conditions.

Coho salmon smolts enter the marine environment in about May and remain and rear within the Strait of Georgia or outside. Beginning in 1995, virtually all juvenile coho salmon left the Strait of Georgia late in their first ocean year and did not return until their spawning migration later in their second ocean year (Beamish et al. 1999). Thus, the collapse of the recreational fishery resulted from this behavioural change during their first marine winter as well as a decline in marine survival from about 10% in the late 1970s to about 1% in the 1990s (Beamish et al. 2010). Our discussions with First Nations Elders on Vancouver Island indicate that historically the presence of coho salmon in the Strait of Georgia in all months was typical and that these fish were so numerous they could be readily caught throughout the year. Thus, the migration out of the Strait of Georgia beginning in 1995 represented a behavioural change that was unprecedented.

In this study, we show that abundances of coho salmon occurred within the Strait of Georgia in the winter of 2017–2018 for the first time since 1994. These fish remained in the strait until they returned to their natal rivers. We speculate that the change in migratory behaviour was related to improved growth in the early marine period in the Strait of Georgia.

Methods

Surveys examining the distribution and abundance of juvenile salmon in the Strait of Georgia have been conducted in the early summer (June/July) and early fall (September) each year since 1998. The standard track line extending from Cape Mudge in the northern Strait of Georgia to the Canada/US border in the south is surveyed (Fig. 1). The surveys use a modified mid-water trawl with a mouth opening of approximately 14m deep by 30m wide and with small mesh cod-end designed to retain juvenile salmon. Fishing occurs at 15m depth intervals from the surface to 60m head-rope depth and sets are typically 30 minutes. Detailed information on the survey protocol is provided in Beamish et al. (2000) and Sweeting et al (2003). Random or haphazard samples of juvenile Pacific salmon (30–100 per set) are selected and measured for fork-length (mm). Catch-per-unit-effort (CPUE) is calculated by set and by survey and is standardized to catch per hour.

Stock composition of the coho salmon collected in the Strait of Georgia has been determined using DNA analysis since 2008. DNA analysis is conducted using a small piece of fin tissue collected during sampling and stored in 95% ethanol. The analysis is conducted at the Molecular Genetics Laboratory at the Pacific Biological Station in Nanaimo, BC following the procedures described in Beacham et al. (2012).

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In addition to samples collected from the annual trawl surveys, information was collected from a group of recreational anglers. This small group of recreational anglers joined together in 2014 to report on Pacific salmon fishing in the Strait of Georgia and to provide tissue samples for DNA analysis of coho and Chinook salmon. Their observations are the only information about the winter residence of Pacific salmon in the Strait of Georgia. Their sampling is opportunistic and their effort is not quantifiable, however, it is knowledge provided by experienced individuals.

Results and Discussion

The distribution of the catch of juvenile coho salmon in September did not change substantially over the 20-year survey period with coho salmon captured throughout the study region but with the greatest numbers in the northern portion of the strait (Fig. 2). The catch of juvenile coho salmon in the September trawl surveys declined between 1998 and 2008 (Fig. 3). The lowest catch was recorded in the survey in 2008 with less than 5 juvenile coho salmon captured per hour (Fig. 3). Following 2008, the catch of coho salmon began to increase. From 2012 and 2017, four of the largest catch years in the 20-year survey period were recorded (Fig. 3). In 2016, the survey was conducted in late October due to issues with the research vessel, and results from this delayed survey are not included in this analysis.

![Fig. 1. Map showing location of the Strait of Georgia and location of standard survey track lines (red line) fished each year during the juvenile salmon surveys.](image1)

![Fig. 2. CPUE by set of coho salmon in September 2014 as an example of general distribution patterns. X’s indicate sets conducted with no coho salmon captured. This distribution pattern is typical of September with coho captured throughout the study area but with larger concentrations in the northern portion of the strait](image2)

![Fig. 3. CPUE (catch per hour) of coho salmon in the September trawl surveys 1998–2017 showing declining trend 1998 to 2008 (R²=0.661) and increasing trend since 2008 (R²= 0.487). 2016 is excluded due to delayed timing of survey.](image3)
Concurrent with the increasing catch of coho salmon in September following 2008, there has been an increase in the length of the juveniles. Between 1998 and 2008 there was no trend in the average size of the juvenile coho salmon. Since 2013 the average size of the juveniles has been above the 20-year average in every year (Fig. 4). An analysis of variance (ANOVA) showed significant differences in the lengths ($F(18, 19846) = 269.9, p<0.001$). A post hoc Tukey test showed that the average lengths of the juvenile coho salmon in 2013 to 2017 was significantly greater than each of the 16 years prior ($p <0.001$).

Beginning in 2013, we received reports from the anglers that coho salmon were in the southern strait near the mouth of the Fraser River in the late winter. Estimates of abundances are only guesses, but based on their reports it appears that the numbers of coho salmon in the late winter have been increasing since 2013.

**Fig. 4.** The anomaly of fork length from the 20-year average for coho salmon during their first September at sea.

In September 2017, the catch and average size of juvenile coho salmon in the trawl surveys remained above average. The stock mixture was dominated by lower Fraser River, Howe/Burrard and east coast Vancouver Island (ECVI) coho salmon representing about 30%, 24%, and 22% of the catch respectively. In addition, smaller numbers of coho salmon from other regions of the Fraser River (12%) and Puget Sound (9%) were captured (Fig. 5).

**Fig. 5.** The stock composition of coho salmon captured in September 2017 in the trawl survey and in February 2018 by the anglers. ECVI—east coast Vancouver Island; Howe/Burrard—Howe Sound and Burrard Inlet region on southern BC mainland coast; Lower FR—lower Fraser River; Other Fraser—all areas of Fraser River above lower Fraser River combined; USA—Puget Sound and Washington State; Other—BC mainland coast north of Howe/Burrard Inlet.
In January 2018, anglers reported large abundances of coho salmon in the central Strait of Georgia. There were reports of coho salmon jumping and densities so large that the frustrated anglers frequently caught coho salmon as they tried to get their lines into deeper water to catch Chinook salmon. In February 2018, anglers collected tissue samples for DNA analysis from 213 coho salmon. The schools being fished were distributed throughout the western side of the central Strait of Georgia with some individual schools estimated to be several km wide and fish within these schools distributed from the surface to 60 m. The stock composition of these fish collected by the anglers was virtually identical with the observations in the trawl survey five months earlier (Fig. 5).

Prior to 1995, wild and hatchery-reared coho salmon from rivers flowing into the Strait of Georgia were caught in their second ocean year in the strait and off the west coast of Vancouver Island. The percentage caught in the two areas varied among years with a weak relationship to the surface salinity in the Strait of Georgia in February (Beamish et al. 1999). Movement out of the strait occurred before February, so the salinity relationship was an indicator of an effect of earlier ocean conditions. The similar behaviour of hatchery and wild fish showed that the migration response likely was related to a metabolic process common to all coho salmon. The movement of virtually all ocean-age-1 coho salmon offshore beginning in 1995 also shows that there were not migratory and non-migratory types as proposed by Healey (1978). Thus, we propose that there was a mechanism that regulated the migratory behaviour of the juvenile coho salmon that was related to metabolic processes and the mechanism would need to be queued by external events.

The increased trend in average lengths and CPUE beginning in September 2013 shows that it is likely that prey abundances were increasing, allowing more energy to be available for growth. We propose that in 2017, the growth increases were sufficient to allow some individuals to remain in the Strait of Georgia. For this to happen, it is possible that the increases in average length that started in 2013 resulted in growth in 2017 that enabled some fish to exceed a metabolic threshold at a critical time in their development. The importance of metabolic thresholds in the development of fishes is discussed by Beamish (2018) and is the basis of the critical size-critical period hypothesis by Beamish and Mahnken (2001). Importantly, it is the faster-growing individuals (that could also be larger) that become resident. The individuals that were smaller at the critical period would not exceed a metabolic threshold and would be programmed to migrate out of the Strait of Georgia in the fall, presumably in search of better feeding opportunities. According to this hypothesis, the inshore and offshore migratory behaviour prior to 1995 would also reflect the percentage of fishes that did or did not exceed the metabolic threshold at the critical period of development. The relationship with the February salinity in the Strait of Georgia could relate to reduced prey abundances when winds forced more Fraser River water to be retained in the Strait of Georgia. The movement of virtually all juveniles out of the strait beginning in 1995 could also result from an extreme reduction in prey abundances with virtually all fish not exceeding a metabolic threshold. It was in the early 1990s that production of Fraser River sockeye salmon also started to decline (Beamish et al. 2012), possibly indicating that a large-scale decline in prey abundance was occurring at the time smolts were entering the ocean.

One difficulty with our interpretation is that the length anomalies in Figure 4 do not show a gradual increase from 2013 to 2017. The critical size-critical period hypothesis includes a possibility that fish not exceeding a metabolic threshold will continue to use more energy for growth and store fewer lipids (Beamish et al. 2008; Beamish et al. 2018; Beamish 2018). According to this speculation, it would not be until 2017 that large numbers of fish exceeded the metabolic threshold and thus were not metabolically programmed to migrate offshore. Beamish et al. (2008) found that growth of juvenile coho salmon in the Strait of Georgia between July and September was inversely related to marine survival suggesting that coho salmon that were larger in July grew less and survived better because they were storing more lipids than the smaller fish. It is also possible that beginning in 2013 there were coho salmon resident within the Strait of Georgia throughout the winter, but the abundances were low and not noticed by the recreational anglers.

Our interpretation of the factors affecting the migratory behaviour of juvenile coho salmon can be tested by comparing the otolith daily growth zones of juveniles that are now resident with the fish from the same brood year that migrate offshore. This could not be done from 1995 to 2017 as coho salmon were not resident. Individuals that are now resident would have wider daily growth zones up to the critical period than those that migrate offshore later in their first ocean year. The daily growth zones in the otoliths of the resident fish may be narrower after the critical period as the fish begin to store lipids and use less energy for growth. The concept that the behavioural change in 1995 and the outside-inside abundances prior to 1995 are a consequence of a metabolic regulated threshold that is cued at a critical time in development is similar to the process that must occur at the time coho salmon are ready to smolt. It is well known that juvenile coho salmon smolt at a number of freshwater ages and that the metabolic decision to smolt is considered to be related to energy storage (Sandercok,
1991; Quinn 2005; Beamish et al. 2018). We are proposing that similar to the process that regulated smolting, there is a metabolic threshold that regulates the migration patterns of the coho salmon during their first marine winter.

REFERENCES


Unravelling how Climate and Competition Shape Sockeye Salmon Dynamics Across the Northeast Pacific Ocean

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Keywords: sockeye salmon, competition, ocean warming, survival, life history diversity

It is well known that both ocean conditions and inter- and intra-specific interactions can influence salmon growth and survival. However, to date, there has been little analysis of the potential mediating effects of ocean conditions on density-dependent interactions among salmon at sea. Such mediating effects may occur, for example, as a result of climate-induced reductions in growth during early marine life leading to increased sensitivity to density-dependent effects later in marine life. Alternatively, favorable ocean conditions during early marine life may mask the detection of density-dependent interactions or mediate their potential effects. Life-history diversity (e.g., variable age at ocean entry), may also influence the effects of ocean conditions and competition at sea on sockeye survival by spreading the consequences of negative climate or competitive interactions across multiple life histories within a given brood year. However, how and when life-history diversity mediates the influence of the conditions salmon experience at sea has also received little attention to date.

In this study, we set out to quantify how a warming ocean, and increasing competition with other salmon, interact to determine the survival of sockeye across their range, and how life history diversity mediates the effects of density-dependent interactions among salmon at sea. We compiled data from 46 sockeye salmon populations across the eastern North Pacific Ocean, spanning a broad geographic range of ocean entry points and life history diversity. We also compiled information on indices of ocean conditions during early marine life (SST anomalies within 400 km of each population’s ocean entry point) and potential salmon competitors (total north Pacific pink salmon abundance). We then fit Bayesian hierarchical models to these data to estimate both the stock specific and region-wide effects of ocean conditions, competition and an interaction between the two on sockeye salmon productivity. We found that the productivity of sockeye from the southern portion of their range was inversely correlated with both ocean conditions and the abundance of competitors and that the effects of competition were stronger when the ocean was warmer. Conversely, for sockeye from the northern portion of their range, we found that productivity was positively correlated with a warming ocean and that there was limited evidence for a negative effect of competition.

We also examined empirical data to evaluate whether variation in smolt-age mediated the effects of competition. We found that that the estimated effect of competition on individual Sockeye salmon populations tended to become weaker (i.e., less negative) as the degree of variation in age at ocean entry increased.

Our findings provide a macroecological foundation upon which to consider how interactions among a changing ocean, inter-specific competition, and the erosion of life history diversity may shape the dynamics of sockeye salmon populations across the eastern North Pacific.
Climate Change and Pacific Salmon Productivity on the Russian Far East

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Keywords: Pacific salmon, climate variability, climate indices, stock abundance

Climate change impact is a mainstream topic in Pacific salmon stock dynamics research. Numerous studies analyze correlations of some salmon species or stock abundance conditions with one or another climate index. Meanwhile, it is evident that no one factor impacts salmon or their environment separately from other elements of the salmon ecosystem. To understand the importance of the contributions of the main physical elements into changing environmental conditions of salmon ecosystems in the North Pacific Ocean, we tried to evaluate correlations between commercial catches of several salmon species with the most popular climate indices. These indices characterize large-scale meteorological, oceanographic, and cosmo-physical processes defining the Earth’s climate. Climate change impacts on Pacific salmon (pink, chum, and sockeye) productivity was assessed based on long-term (1971–2015) fisheries statistics and dynamics of 18 climate indices using stepwise multivariate regression analysis. Three regional stock groups were analyzed: Eastern Kamchatka and Chukotka (BPG), Western Kamchatka and continental coast (NOG), and Sakhalin, Kuriles, Amur River, and Primorye (SOG).

We analyzed salmon catch dynamics in numbers to avoid an influence of fluctuating average salmon body weight. Pink salmon heavily contribute to the total Russian commercial salmon catch, and its predominance is illustrated further when the numbers from catches are reviewed (Fig. 1). Portions of chum and sockeye salmon increased in the last few years, when their commercial catches by Russia regularly reached 100,000 metric tons for chum and 45,000 metric tons for sockeye. If we consider salmon catch dynamics by regional groups and by species, the three selected regional groups contributed comparable portions of the total catch. While the left parts of histograms demonstrate significant interannual variability determined by the interchange of odd- and even-year pink salmon broodlines with different productivity, the right parts show a trend to levelling. The contribution of the NOG and SOG regional stock groups is much more significant for pink and chum salmon. Commercial catch increase is mostly determined by the SOG regional stock group, especially for chum salmon.

Table 1. Correlation matrix of relationships between climate indices used in this study, 1971–2015. Correlation coefficients \((r)\) are shown below mid-line, confidence probability \((p)\) — above mid-line.

<table>
<thead>
<tr>
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<th>NP</th>
<th>AO</th>
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<th>NPI</th>
<th>AO</th>
<th>PDO</th>
<th>N.P.HEMISP</th>
<th>SSI</th>
<th>OLR</th>
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Remarks: Significant correlation coefficients \((p < 0.05—0.001)\) are highlighted in bold. Number of data values available for each index, \(N = 44\) for ALPI, PNA, NP, AO, AFI, PDO, N.P.HEMISP, Nino 3.4, GLB.Ts+dsST, SSF, AP, SSI, and OHC-700 indices, \(N = 44\) for LOD, \(N = 39\) for BSI and OLR, and \(N = 34\) for AFI and PCI.

A set of eighteen climate indices with different dynamics may also be conditionally divided by three groups. The meteorological indices include the Aleutian Low Pressure Index (ALPI), the North Pacific Index (NPI), the Atmospheric Forcing Index (AFI), the Pacific-North American Oscillation (PNA), the Arctic Oscillation (AO), and the West Pacific Teleconnection Index (WP). Oceanological indices examined in this study include the Pacific

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Decadal Oscillation (PDO), GLOBAL Land-Ocean Temperature Index (LOTI), the Bering Sea Ice Cover Index (BSI), the Northern Hemisphere Land and Sea Temperature Anomalies (N.HEMI+dSST), Nino 3.4 Index, and the Global Ocean Heat Content for the upper 700-meter layer (OHC-700). The three indices that are calculated using sea surface temperature (SST), N.HEMI+dSST, LOTI, and OHC-700, have similar positive trends, which reflect growing temperature of the ocean surface layer, as well as progressive heat accumulation (Levitus et al. 2005).

The third group consists of cosmo-physical indices including the Solar Flux (SFI) and the Solar Spot (SSI) Indices, the Geomagnetic Disturbance Index (Ap), Length of the Day (LOD), Outgoing Longwave Radiation Index (OLR), and the Winter Pacific Circulation Index (PCI). The last index may be included into the meteorological group. It is calculated as the sum of the negative anomalies of the northwestern transport of air masses. The higher index means the stronger southwest inflow to the coast of North America and increases in heat influx. This relates it to the SST-related oceanological indices with the well-expressed positive trend since 1975, which were mentioned earlier. Index values were averaged using a moving average technique over a two-year period for comparisons with pink salmon catch dynamics, and over a four-year period for sockeye and chum salmon.

Results of correlation analysis of the relationship between climate indices based on 1971–2015 data showed that about 30% of correlations occurred were significant (Table 1). The highest positive correlation coefficients are observed between the SST-related oceanological indices, in pairs of them and with the WP index, between the SFI and SSI, and also between the AFI and ALPI. The strongest negative correlations are observed between the LOD and the SST-related oceanological indices, as well as WP, and between the OLR and the Nino 3.4 indices. The latter is rather understandable since the higher Nino 3.4 Index characterizes a situation when the cold Peruvian Current is well developed and transports relatively cold waters to the equatorial region, while the OLR characterizes the heating of surface waters and the intensity of evaporation near the equator.

Table 2. Pearson’s correlation coefficients (r) and confidence probability (p) between salmon commercial catches of different regional groups (nearshore and in-river fisheries on the Russian Far East, 1,000 fish) and annual values of eighteen selected climate indices, 1971–2015.

<table>
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<tr>
<th>Indices</th>
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<th>Chum salmon</th>
<th>Sockeye salmon</th>
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<tr>
<td>WP</td>
<td>0.07</td>
<td>0.068</td>
<td>0.07</td>
</tr>
<tr>
<td>N.HEMI+dSST</td>
<td>0.34</td>
<td>0.034</td>
<td>0.031</td>
</tr>
<tr>
<td>LOD</td>
<td>-0.05</td>
<td>0.758</td>
<td>-0.04</td>
</tr>
<tr>
<td>Nino 3.4</td>
<td>0.33</td>
<td>0.036</td>
<td>0.31</td>
</tr>
<tr>
<td>GLB1+dSST</td>
<td>0.33</td>
<td>0.036</td>
<td>0.31</td>
</tr>
<tr>
<td>BSI</td>
<td>-0.10</td>
<td>0.523</td>
<td>0.10</td>
</tr>
<tr>
<td>OHC-700</td>
<td>0.35</td>
<td>0.037</td>
<td>0.33</td>
</tr>
<tr>
<td>SSF</td>
<td>-0.11</td>
<td>0.503</td>
<td>-0.07</td>
</tr>
<tr>
<td>Ap</td>
<td>-0.32</td>
<td>0.043</td>
<td>-0.24</td>
</tr>
<tr>
<td>SSI</td>
<td>-0.15</td>
<td>0.347</td>
<td>-0.10</td>
</tr>
<tr>
<td>OLR</td>
<td>0.20</td>
<td>0.202</td>
<td>0.14</td>
</tr>
<tr>
<td>LOD</td>
<td>-0.17</td>
<td>0.278</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

Remark: Casewise deletion of missing data is applied.

The correlation analysis was a primary stage in determining the relationships between the productivity of Pacific salmon and climate variability. Index selection was based on correlation coefficients having a weak (from 0.3 to 0.5), moderate (from 0.5 to 0.75) or a higher level of significance. The minimum number of significant correlations are observed between the climate indices and commercial catches of pink salmon (Table 2). Correlations with a moderate level of significance are calculated for the SOG only. Positive correlations are observed between pink salmon catch and the SST-related oceanological indices, while negative ones are observed with the Ap and LOD indices. For chum and sockeye salmon, moderate and strong “index–catch” relationships are noted in most cases. For all regional groups and even for all salmon species under consideration, relationships with climate indices have the same negative or positive sign. Based on the results of correlation analysis, it may be concluded that pink salmon is least affected by climate change impacts while chum and sockeye salmon are affected...
almost to the same degree. This may be due to the shorter duration of marine phase for pink and similar duration of the marine phase for two other salmon species.

Table 3. Results of multivariate regression modelling of pink salmon commercial catches of different regional groups (nearshore and in-river fisheries on the Russian Far East, 1,000 fish) and annual values of ten selected climate indices, 1971–2015.

<table>
<thead>
<tr>
<th>Regional group of stocks</th>
<th>Multiple regression result</th>
<th>Regression summary for dependent variable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>BPG</td>
<td>0.38</td>
<td>0.14</td>
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<tr>
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<tr>
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<tr>
<td>SOG</td>
<td>0.75</td>
<td>0.56</td>
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<tr>
<td>NOG</td>
<td>0.36</td>
<td>0.13</td>
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<tr>
<td>Far East</td>
<td>0.74</td>
<td>0.55</td>
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Remarks: Statistical parameters: $R$—coefficient of multivariate regression, $R^2$—determination coefficient, $SE$—standard error, $F$—$F$-criterion, $df$—degrees of freedom for each regression, $p$—confidence probability, $b_0$—constant term or the axis $y$ intercept, $b_1$, $b_2$—regression coefficients, Beta and $B$—standardized and non-standardized regression coefficients (“weights”). $N = 45.$

To select climate indices that are more relevant for future use, we reduced the number of variables based on factor analysis. A set of ten climate indices with dynamics in a good agreement with fluctuations of Pacific salmon catches were selected by correlation analysis: ALPI, PNA, WP, PDO, NP, AO, N.HEMI+dSST, Ap, SSI, and LOD, which were used for the multivariate regression analysis. Results of multivariate regression modelling of pink salmon catches with mean annual values of climate indices are presented in Table 3. The lowest values of regression coefficients are received for pink salmon, which imply a weak correlation between productivity: $R = 0.38$ for BPG, 0.36 for NOG, and 0.75 for SOG. Significant relationships exist with four climate indices, N.HEMI+dSST, PDO, Ap, and SSI, and the strongest one, between catches in SOG and the N.HEMI+dSST index. For all regional groups, N.HEMI+dSST reflects the strongest effect of positive near-surface air temperature and SST anomalies on pink salmon productivity: beta coefficient varies from 0.24 to 0.60. In SOG, PDO reflects the negative effect of negative winter SST anomalies in central and western North Pacific: beta coefficient = -0.35.

Moderate to high values of regression coefficients are received for chum salmon: $R = 0.71$ for BPG, 0.93 for NOG, and 0.86 for SOG, and sockeye: 0.91–0.92 for BPG and NOG, respectively (Tables 4–5). The strongest correlations for two of three regional chum stocks groups and for one sockeye group are observed with the Ap index that reflects a negative effect of positive geomagnetic disturbance anomalies: beta coefficients ranged -0.37 to -0.25 for chum and -0.14 to -0.42 for sockeye. Ap is a measure of the general level of geomagnetic activity over the globe for a given day. It is derived from measurements made at eleven stations worldwide of the variation of the geomagnetic field due to currents flowing in the earth’s ionosphere and, to a lesser extent, in the earth’s magnetosphere. In its physical sense, the Ap is an overall measure of solar wind-magnetosphere interactions and is usually used in correlation studies of interplanetary and solar phenomena. The N.HEMI+dSST indicator reflects the strongest effect of positive temperature anomalies: beta coefficients ranged 0.65–0.91 for chum and 0.61–0.85 for sockeye. The significance of indices for the BPG and NOG groups of chum and sockeye salmon is the opposite. Likely, there is a connection with Saito and Miyakoshi’s (2018) observations, who emphasized the significance of SST dynamics for chum salmon survival in the Sea of Okhotsk. Proceeding from results of multivariate regression modelling, it may be concluded that the thermal conditions of upper water layer and dynamics of solar activity are the major drivers of these three species of Pacific salmon productivities in the North Pacific Ocean (Radchenko et al. 2007; Bugaev et al. 2016).
Table 4. Results of multivariate regression modelling of chum salmon commercial catches of different regional groups (nearshore and in-river fisheries on the Russian Far East, 1,000 fish) and annual values of ten selected climate indices, 1971–2015.

<table>
<thead>
<tr>
<th>Regional group of stocks</th>
<th>Multiple regression result</th>
<th>Regression summary for dependent variable</th>
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<tbody>
<tr>
<td></td>
<td>$R$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>BPG</td>
<td>0.71</td>
<td>0.51</td>
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<tr>
<td>SOG</td>
<td>0.86</td>
<td>0.74</td>
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<tr>
<td>NOG</td>
<td>0.93</td>
<td>0.86</td>
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</table>

See remarks in Table 3.

Table 5. Results of multivariate regression modelling of sockeye salmon commercial catches of different regional groups (nearshore and in-river fisheries on the Russian Far East, 1,000 fish) and annual values of ten selected climate indices, 1971–2015.

<table>
<thead>
<tr>
<th>Regional group of stocks</th>
<th>Multiple regression result</th>
<th>Regression summary for dependent variable</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$R$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>BPG</td>
<td>0.91</td>
<td>0.82</td>
</tr>
<tr>
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<tr>
<td>NOG</td>
<td>0.92</td>
<td>0.85</td>
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See remarks in Table 3.
Fig. 1. Commercial catch of Pacific salmon (nearshore and in-river fisheries) in the Russian Far East by species and selected regional stock groups, 1971–2016.

Fig. 2. Distribution of the Pearson's correlation coefficient values between pink salmon commercial catches (1,000 fish) by regional stock groups and SST anomalies in salmon first marine autumn (left panels) and winter (right panels). Regional stock groups: A—BPG, B—SOG, and C—NOG.

Fig. 3. Distribution of the Pearson's correlation coefficient values between chum salmon commercial catches (1,000 fish) by regional stock groups and SST anomalies in salmon first marine autumn (left panels) and winter (right panels). Regional stock groups: A—BPG, B—SOG, and C—NOG. Circles size—as on Fig. 2.
After we determined the main drivers of Pacific salmon productivity, we tried to explore their influence in the geographical aspect. To analyze the interannual variability of the temperature conditions in the areas of autumn and winter salmon feeding migrations, a conditional division of the Northern Pacific into 39 cartographic trapezoids was carried out with a longitude step of 10° and a latitude step of 5°. We built distribution maps of Pearson correlation coefficient ($r$) for the statistical relationship between commercial salmon catches by regional groups and SST anomalies during the autumnal outmigration (September–November) and wintering (December–February) of salmon juveniles in their first year at sea. Satellite monitoring data from 1982–2015 was used. Catches in numbers were calculated in view of the age of maturity and spawning return (0.1 for pink, 0.3–0.4 for chum, and n.2–n.3 for sockeye). Satellite SST data was used from those regions only, where autumn and winter migrations of Pacific salmon from the Far Eastern stocks migrate during the first year of their marine residence.

During the oceanward migration of juvenile pink salmon in September–November, the highest positive correlation between the SST anomalies and catch value was observed for the SOG group of stocks. These positive correlations are observed in the central and southern part of the Sea of Okhotsk, as well as in the Kurile Islands’ waters in the Pacific Ocean (Fig. 2). The Pearson correlation coefficients in these regions range from 0.52 to 0.70. While weak positive correlations are noted for the BPG pink salmon throughout their migration areas, no significant correlations are found for the NOG since juvenile pink salmon originated from this region leave the Sea of Okhotsk earlier and are smaller than pink salmon that originated from the southern areas. Conversely, moderate correlations for the NOG are observed in the northwestern Pacific in December–February. The maximum coefficients reach a level of $r = 0.3–0.4$. No significant correlations were found for two other regional groups of pink salmon stocks. This explains why the strength of the relationship between the total Russian pink salmon catch and heat budget of the upper ocean layer, which was revealed in mid-2000s, weakens with a growth of the Bering Sea and Western Kamchatka contributions into the total pink salmon harvest in Russia.

An anomalously warm temperature regime of the waters during the autumn migration of juvenile chum salmon promotes productivity of stocks in all three groups during their migrations in the central and southern Okhotsk Sea, the south-western Bering Sea, and the Pacific waters along the Kuril Islands and Kamchatka Peninsula (Fig. 3). The maximum correlation coefficients vary in a range of $r = 0.4–0.6$. In winter, the strength of the relationship weakens with an expansion of the chum juveniles’ distribution along the Subarctic Current front. It is remarkable that the distribution of positive and negative correlation coefficients reflects a typical position of two water domains with opposite SST anomalies on the well-known illustration of the PDO model (Mantua et al. 1997).

### Table 5.

Results of multivariate regression modelling of sockeye salmon commercial catches of different regional groups (nearshore and in-river fisheries on the Russian Far East, 1,000 fish) and annual values of ten selected climate indices, 1971–2015.

<table>
<thead>
<tr>
<th>Regional group of stocks</th>
<th>Multiple regression result</th>
<th>Regression summary for dependent variable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>BPG</td>
<td>0.91</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>$b_1$ (Ap)</td>
<td>-0.42</td>
</tr>
<tr>
<td></td>
<td>$b_2$ (WM)</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>$b_3$ (LOD)</td>
<td>-0.21</td>
</tr>
<tr>
<td></td>
<td>$b_4$ (AO)</td>
<td>0.44</td>
</tr>
<tr>
<td>NOG</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>$b_1$ (N.HEMI+65ST)</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>$b_2$ (ALP)</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>$b_3$ (WM)</td>
<td>-0.17</td>
</tr>
<tr>
<td></td>
<td>$b_4$ (LOD)</td>
<td>-0.32</td>
</tr>
<tr>
<td></td>
<td>$b_5$ (AO)</td>
<td>-0.46</td>
</tr>
<tr>
<td></td>
<td>$b_6$ (SSD)</td>
<td>0.25</td>
</tr>
<tr>
<td>Far East</td>
<td>0.93</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>$b_1$ (N.HEMI+65ST)</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>$b_2$ (Ap)</td>
<td>-0.44</td>
</tr>
<tr>
<td></td>
<td>$b_3$ (PNA)</td>
<td>-0.07</td>
</tr>
<tr>
<td></td>
<td>$b_4$ (WM)</td>
<td>-0.17</td>
</tr>
<tr>
<td></td>
<td>$b_5$ (AO)</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>$b_6$ (SSD)</td>
<td>0.11</td>
</tr>
</tbody>
</table>

See remarks in Table 3.
Sockeye salmon also show the same pattern of correlation coefficients distribution. The Pearson correlation coefficients for juvenile sockeye in September–November range from 0.4 to 0.7 (Fig. 4). In winter, relationships are much weaker for the NOG than for the BPG. In general, the direct interrelation between chum and sockeye salmon productivity and the temperature is observed in a period of autumnal outmigrations while it has divergent trends in the winter.

**Fig. 4.** Distribution of the Pearson's correlation coefficient values between sockeye salmon commercial catches (1,000 fish) by regional stock groups and SST anomalies in salmon first marine autumn (left panels) and winter (right panels). Regional stock groups: A—BPG, B—SOG, and C—NOG. Circles size—as on Fig. 2.

In conclusion, the heat budget of the upper water layer and dynamics of solar activity seem to be the major drivers of Pacific salmon productivity in the North Pacific Ocean. For all regional groups and all salmon species under consideration, the N.HEMI+dSST index reflects the strongest effect of positive near-surface air and sea surface temperature anomalies on salmon productivity, especially for chum and sockeye salmon. Negative relationships with the Ap index dynamics reflect a negative effect of enhanced geomagnetic disturbances on salmon stocks' productivity. Distribution of positive and negative correlation coefficients between SST anomalies and chum and sockeye salmon productivity delineates a typical position of two water domains with opposite SST anomalies on the PDO model. This emphasizes the significance of the PDO index as a proxy to forecast the climate change impacts on salmon productivity.

**REFERENCES**


Toxic “bloom” and Pacific Salmon (Catch, Spawning Migrations, Production) in the Far Eastern Seas of Russia—Are There New Risks?

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2Zhirmunsky Institute of Marine Biology, National Scientific Center of Marine Biology, Far Eastern Branch, Russian Academy of Sciences, Pal’chevsksy str., 17, Vladivostok, 690041, Russia

3Far Eastern Federal University, Sukhanova street, 8, Vladivostok 690950, Russia

Keywords: Toxic “bloom”, Pacific salmon, Far Eastern seas of Russia

“Red tide” was again observed in Olyutorsky Gulf in July 2017. This specific phenomenon was successfully studied in detail for the first time due to the concern and consequent interest of commercial fishermen whose trade nets appeared to be in the “bloom” zone. Having carried out species definition of the microalgae on the basis of morphology we stated that the “bloom” was caused by dinoflagellates from Alexandrium tamarense-species-complex. The taxonomic position of Alexandrium was more exactly defined by molecular-genetic analysis, ascertaining that the sample contained essentially a monoculture of A. fundyense (Balech) (Group I ribotype, previously known as the North American ribotype) from the above-mentioned complex. The number of dinoflagellates in the sample was estimated. On the basis of the satellite data, the “bloom” development dynamics were reconstructed using the chlorophyll-a accumulation. The presence of saxitoxin was revealed in the water sample that contained the suspension of Alexandrium cells. We collected information on unusual behavior of pink salmon which entered the zone of the “bloom”, on peculiarities of the seabirds’ behavior, on the air quality in the near-shore area; on weather conditions prior to and during the “bloom”; and the contents of the biogenic elements in the coastal water at the beginning of the “bloom”. Also, on the basis of the satellite data the dynamics of surface water temperature in the coastal zone of Olyutorsky Gulf were reconstructed. The population rate of spawning areas in main rivers of reproduction of pink salmon and chum salmon in the basin of Olyutorsky Gulf–Apuka–and terminal neighboring rivers was estimated by air search (Lepskaya et. al. 2017, 2018).

The analysis of the data obtained revealed the following set of questions:

- How close to each other are the areas of reproduction and catch of the Pacific salmon and the zones of “bloom” including toxic ones? Do they overlap?
- Do the toxins produced by harmful microorganisms directly impact fish of the genus Oncorhynchus?
- How does the quality of raw material change in the case of the influence of harmful microalgae on salmon?
- Can coastal “blooms” of harmful microalgae cause a sudden and thus unpredictable decrease of productivity of the areas of reproduction of Pacific salmon?
- What are the conditions of formation of the “toxic blooms”?
- Is it possible to forecast the “toxic blooms”? What might be their expected frequency in conditions of retention of a warming trend in the North-western Pacific?

How close to each other are the areas of reproduction and catch of the Pacific salmon and the zones of “bloom” including toxic ones? Do they overlap?

“Red tides” are not rare in the Far Eastern seas (Konovalova 1993, 1999a). Studies in the 1980–2000s showed that “red tides” at the Pacific coasts of Russia were often caused by dinoflagellates of the genus Alexandrium, their concentration being maximal exactly at the eastern coasts of Kamchatka (Fig. 1). Alexandrium can be preserved for a long time in bottom sediments in the form of viable cysts (Fig. 2). In favorable conditions, the cysts are activated and through the process of vegetative reproduction form local or spacious aggregations of vegetative cells, quite often in huge concentrations (Konovalova 1999b). Some species of this genus are able to produce saxitoxin (SXT)—a poison with neuromuscular effects, which cause paralytic intoxication by molluscs (PSP). The species of Alexandrium are also well-known producers of ichthyotoxins (Emura et al. 2004) and allelochemical substances with high inhibition or stimulation effects (Arzul et al. 1999; Tillmann et al. 2008). Harmful/potentially toxic species of Alexandrium periodically have mass reproduction at the coasts of Kamchatka (Fig. 3), overlapping with the areas of fish number formation during key stages of ontogenesis and also catches of large portions of producers of populations of pink salmon, red salmon,
silver salmon and king salmon in the Russian Far East. The portion of the total Far Eastern catches which come from these species is 80%, 93%, 77% and 99% respectively, according to 2017 data (Shuntov and Temnykh 2017).

Fig. 1. Distribution of *Alexandrium* near Pacific shore of Russia (Selina et al., 2006 with additions by Lepskaya—pink circles).

Fig. 2. *Alexandrium* cyst concentration in surface bottom sediments near Pacific shore of Russia (Selina et al., 2006).

Fig. 3. Distribution of toxic, potentially toxic (red circles) and non-toxic (green circles) red tides (Konovalova, 1993).

Fig. 4. Areas of reproduction and catching of some *Oncorhynchus* species in Kamchatka.

Information on the influence of toxic “blooms” on aquatic bioresources and coastal biota of the Peninsula is limited and fragmentary because of sparsely populated sea coasts. For instance, Lobkov (1991) proposed that the increase in the number of dead seabirds on the coast of Kronotsky Gulf in odd years was caused by their eating of macrozooplankton which in turn accumulated toxins by feeding on toxic microalgae. Konovalova (1993, 1999b) pointed out that in July 1986 a “bloom” of *Alexandrium tamarense* in Olyutorsky Gulf was accompanied by the death of pinnipeds, fish, and birds.

Toxicity of *Alexandrium* was acknowledged only for the population of this microalga from the Avachinskaya Bay at the beginning of the 1980s when the presence of 11-hydroxysaxitoxin in mussels from this water basin was confirmed (Orlova et al. 2007).

The ability of *Alexandrium* to produce toxins in cultures derived from cysts taken from the bottom sediments of the Kamchatka shelf was confirmed by the works of Orlova and co-authors in 2005 (Fig. 5 and 6) (Orlova, 2005, 2007).

We managed to extract saxitoxin in concentration of 330 mkg/l only in 2017 (Lepskaya et al. 2017) from the
water sample containing the suspension of *Alexandrium* cells, which was taken by fishermen at the coasts of Olyutorsky Gulf during the July water “bloom”. It should be noted that in the paper by Lepskaya et al. (2018) there was a technical error, and a concentration of saxitoxin of 0.33 mg/l was published incorrectly.

Thus, such areas of migration and catch of Pacific salmon as Avachinskaya Guba Inlet, Olyutorsky and Karaginsky Gulfs get into the zone of potential toxic impact of microalgal “blooms”. The beginning and dynamics of the fishery, as well as the total catch of Pacific salmon are unknown for the Olyutorsky and Karaginsky Gulfs. As for Avachinskaya Bay, there is large-scale poaching of Pacific salmon and invertebrates, the volume of which is very difficult to figure out.

The microalgal “blooms” are not marked in the remaining regions of the Eastern Kamchatka, for example, in the Kamchatsky Gulf.

Despite the fact that concentration of *Alexandrium* in some parts of Kamchatka portion of the Sea of Okhotsk coastal water areas reach concentrations of 1000 cells/l or more, it does not form vast aggregations (Lepskaya et al. 2009). This is due to the high dynamic activity of the waters in this area, which prevents stagnant effects from forming (Anon 1993).

Olyutorsky Gulf and possibly its adjacent water areas are the most significant basins of reproduction and catch of Pacific salmon that get into the risk zone. To the west of Olyutorsky Gulf, it is the Korf Gulf, to the East it is the water areas of the Bering and Chukchi Seas, where *A. fundyense* is able to produce saxitoxin, neosaxitoxin, gonyautoxins 1 and 3, and C2 toxin, in cultures, and perhaps *in vitro* (Natsuike et al. 2017).

Do the toxins produced by harmful microalgae directly impact fish of the genus Oncorhynchus?

The unusual behavior of pink salmon was observed in 2017 in the coastal zone of Olyutorsky Gulf where trade nets were located in the belt of “bloom” of *Alexandrium*. According to fishermen, fish that bumped into aggregations of the microalgae were trying to dive under these aggregations or move along their borders in clean water. Also, according to fishermen, the fish that moved through aggregations of *Alexandrium* were “flabby and exhausted” and died soon after. Fish quickly became lethargic in the trade nets. During transport, from nets to the coast in special boats with slots on the bottom, the fish were already dead, “inelastic”.

Such behavior and the state of fish when caught testify to the fact that saxitoxin in the water impacted the nervous system of fish leading to an abnormal state similar to paralysis.

It is known that the motor activity of fish changes under the influence of saxitoxin. These changes can include anomalous (convulsive) swimming, loss of balance (disorientation), full immobility—lethargy with lethal termination (Saito et al. 1985; Turner 1997; Zaccaroni and Scaravelli 2008). Interesting data on the cases and the reason for the mass death of fish, including salmon, caused by HAB, and PSP are presented in the review by Costa (2016).
Besides that, the dwellers of the Pakhachi settlement noted a strong unpleasant smell of “decaying grass” from the seaside and the deserted seashore which is usually full of seabirds.

How does the quality of raw material change in the case of influence of harmful microalgae on salmon?

Passing through the “bloom” zone, fish have complete contact with the toxin released by algae into the water, they have to “breathe in toxic water” and suspended algae, which can also get into their stomachs.

It is shown that Pacific salmon with a long-term period in the marine nursery can accumulate some quantity of saxitoxin in their internal organs, which, in such case passes in food chains from algae via macrozooplankton to fish. For instance, saxitoxin was found in the viscera of spawning chum salmon (Sato et al. 1998).

It was experimentally shown with Atlantic salmon that the concentration of saxitoxin coming from the blood into muscles is less than in other organs and tissues because it is intensively excreted from Atlantic salmon by the liver and kidneys (Bakke and Horsberg 2010).

In the case of the direct impact of saxitoxin on the pink salmon observed in Olyutorsky Gulf in July 2017, the fish probably died before accumulating any significant amount of saxitoxin in the muscles and gonads.

Can coastal “blooms” of harmful microalgae cause a sudden and thus unpredictable decrease of productivity in the areas of reproduction of Pacific salmon?

It seems to us to be quite possible. Let us discuss the situation observed in Olyutorsky Gulf in July 2017, when the estuaries of spawning rivers were closed by the belt of the “bloom” of *Alexandrium*. According to the fishermen, the majority of the fish moved along the borders between the clean and “blooming” water. With these observations, it is possible to suppose that it was impossible for the pink salmon to reach its native river, forcing part of the pink salmon stock to move to terminal rivers that were not closed by the “bloom”. In other words, there was a redistribution of migration streams. As a result, a much smaller number of spawning fish came to the rivers of Olyutorsky Gulf than was expected.

[Fig. 7. Filling of the spawning rivers of Olyutorsky Gulf and Korf Gulf by humpback salmon (% of the total filling rate).]

This conclusion confirms the retrospective analysis of the data of research of pink salmon on the spawning areas of the Korf-Olyutorsky basin (Fig. 7). Filling of the spawning rivers of Olyutorsky Gulf in 2017 by pink salmon was unexpectedly low in the series of odd years, and compared with the last registration year, 2010.

The “bloom” of *Alexandrium* also influenced the pink salmon fishery in Olyutorsky-Karaginsky zone during the peak phase of the runs. Thus, in spite of “the third in number and the second in catch result in the history of Karaginsky pink salmon fishery”, field conditions in the Olyutorsky Gulf were the worst in the region. And the beginning of the fishery shifted from the Olyutorsky Gulf to the central part of Karaginsky Gulf in contrast to the last years (Shevlyakov et al. 2017).

The Olyutorsky Gulf portion of the total catch of pink salmon in Olyutorsky-Karaginsky region since 2005 was 20% (min 9%, max 54%), in 2017 this portion decreased to 5%.

In the last 12 years, catches of pink salmon in the Olyutorsky Gulf have correlated with the total catch of this species in Olyutorsky-Karaginsky region, but in 2017 this correlation was broken (Fig. 8).
Conditions of the formation of "toxic blooms"

There were heavy showers in Olyutorsky Gulf and riverheads of the Pakhacha and the Apuka in early July 2017 that caused a mudflow in the Pakhacha River. A huge quantity of biogenic elements was carried out to the seashore (Table 1). Concentrations of biogenic elements (mean for July) in Avachinskaya Bay, which is exposed to long-term chronic anthropogenic impact, are presented in the Table for comparison.

<table>
<thead>
<tr>
<th>Biogenic element</th>
<th>Olyutorsky Gulf</th>
<th>Avachinskaya Bay</th>
<th>Excess of concentration of biogenic elements in Olyutorsky Gulf as compared to Avachinskaya Guba Inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral phosphorus, mgP/l</td>
<td>0.181</td>
<td>0.049</td>
<td>4</td>
</tr>
<tr>
<td>Ammonium nitrogen, mgN/l</td>
<td>2.637</td>
<td>0.174</td>
<td>15</td>
</tr>
<tr>
<td>Nitrite nitrogen, mgN/l</td>
<td>0.042</td>
<td>0.004</td>
<td>11</td>
</tr>
<tr>
<td>Nitrate nitrogen, mgN/l</td>
<td>+</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Mineral nitrogen, mgN/l</td>
<td>2.68</td>
<td>0.19</td>
<td>14</td>
</tr>
<tr>
<td>Iron, mgFe/l</td>
<td>0.40</td>
<td>0.10</td>
<td>4</td>
</tr>
<tr>
<td>Silicon, mgSi/l</td>
<td>3.0</td>
<td>4.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Fig. 9. The dynamics of warming of coastal waters and concentration of chlorophyll $a$ at the coasts of Olyutorsky Gulf in July 2017.

Besides that, the flood became the probable cause of desalination in the coastal water area. Calm sunny
weather set in the region after the cyclone. The coastal water area started warming (Fig. 9). Light south-western and south-eastern breeze shifted the belts of “blooming” to the shore in the zone of trade nets, which fused in the common field with enormous biomass judging by the amount of chlorophyll \( a \). (Fig. 9). The first spots of colored water appeared before that, about 2 miles from the shore. Calm weather lasted during the entirety of July. Light offshore winds and tidal currents were unable to drive the dense surface layer of microalgae away. Perhaps, some limiting role was played by the trade nets.

Earlier, only two taxa of \textit{Alexandrium}: \textit{A. tamarense} and \textit{A. ostenfeldii} were found in the Olytutorsky Gulf (Selina et al. 2006). Further studies showed that \textit{A. tamarense} represented a complex of morphologically close species, including those that produce saxitoxin and the ones that do not produce this substance (John et al. 2014).

According to our data, species of \textit{Alexandrium tamarense}-complex found on the Kamchatka coasts of the Sea of Okhotsk are considerably more abundant in the desalinated and warm water areas (Lepskaya et al. 2009). However, conditions for activating the “bloom” of toxic species are still unknown.

\textit{Is it possible to forecast “toxic blooms”? What might be their expected frequency in conditions of retention of a warming trend in the North-western Pacific?}

According to the data of G.V. Konovalova (1999b), “red tide” caused by \textit{Alexandrium tamarense} \textit{ex cavata} was recorded in Olytutorsky Gulf in July 1986, and in mid-late July 1988, 1990. The toxic impact of the “bloom” was observed only in 1986 because it was accompanied by the death of pinnipeds, fish, and birds. In the time between 1986 and 2017, i.e., for 31 years, there was no information on the “blooms” and the simultaneous death of animals.

Thus, in spite of the commonness of such phenomenon as “red tides” in the eastern Kamchatka and the Bering Sea, toxic “blooms” are rare and local. It is impossible to predict them and in the opinion of V.V. Bogatov (Keynote at the United Plenary meeting of Scientific Council on hydrobiology and ichthyology RAS, Hydrobiological society of RAS, and Interdepartmental ichthyologic committee “Actual problems of hydrobiology and ichthyology”, 27 March 2018, Moscow), such events may appear more frequently in the “period of climatic extremes”. Their impact may cover larger areas and be longer in time.

\textit{Acknowledgments}—The authors are thankful to the leading scientist of the Laboratory of dynamics of salmon fish number and forecast improvement of KamchatNIROE. A. Shevlyakov for valuable remarks and the leading engineer of Laboratory of chemical analysis of KamchatNIROV. D. Sviridenko for identification of biogenic elements. A molecular-genetic analysis was carried out with a support of RSF (agreement № 14-50-00034).

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Community-based Monitoring Demonstrates Increasing Occurrences and Abundances of Pacific Salmon in the Canadian Arctic from 2000 to 2017

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Keywords: Pacific salmon, Arctic, range extension, climate change, temperature, subsistence harvest

Introduction

Changing environmental conditions have precipitated northward distributional shifts for many marine ectotherms (Sunday et al. 2012). As salmon distributions are linked to species-specific thermal tolerances (Welch et al. 1998), warming trends have also been used to predict northward shifts in salmon species and their habitats (Welch et al. 1995; Kaeriyama 2008; Abdul-Aziz et al. 2011; Yoon et al. 2015). Indeed, Pacific salmon Oncorhynchus spp. appear to be responding to these warming trends as relatively high abundances of juvenile pink and chum salmon were caught in the Chukchi Sea in 2007 (Eisner et al. 2013), and immature chum salmon were found at higher latitudes in the Bering Sea in 2009 (Sato et al. 2012). Although Pacific salmon are not new to the Arctic (Stephenson 2006; Nielson et al. 2013), trends of increasing Pacific salmon harvests in subsistence fisheries in the Canadian Arctic are also apparent (Dunmall et al. 2013). Pacific salmon appear to be naturally accessing Arctic habitats as conditions become more favorable (Babaluk et al. 2000a; Grebmeier et al. 2006), which contributes to the perception of the Arctic as a conservation haven for salmon in a warming environment (Rand et al. 2012).

The Arctic, however, is vast, remote, and sparsely populated. It is exceedingly difficult, therefore, to detect and monitor widening geographic presence and increasing abundance trends of rare species in such an environment. Salmon, which are occasionally harvested as bycatch in subsistence fisheries across the Canadian Arctic, may be acting as effective indicators of climate warming by shifting distributions northward in response to environmental change (Dunmall et al. 2013; Dunmall 2018). By developing a community-based monitoring program, called Arctic Salmon, that responds to community-driven interest and questions about increasing salmon harvests, it is possible to document trends in salmon abundance in the Canadian Arctic. This information guides research to better understand the environmental factors influencing distributional shifts of marine species northward and can be used to assess the risks and opportunities associated with increasing salmon in the Canadian Arctic.

Here the objective is to summarize changes in salmon abundance, distribution and species composition in subsistence harvests in Canadian Arctic since previous reviews (Stephenson 2006; Nielson et al. 2013; Dunmall et al. 2013). This information also contributes to the establishment of community-based monitoring as an effective method to detect rare fish species across a vast and remote geographic area, and highlights the role of salmon as a sentinel useful to monitor a rapidly changing Arctic.

Methods

A Pacific Salmon Collection Program was established by Fisheries and Oceans Canada in 2000 to monitor increased harvests of Pacific salmon in subsistence fisheries in the Northwest Territories. This program was expanded as Arctic Salmon in 2011 and is now a community-based monitoring tool tracking distribution and relative abundance changes for Pacific salmon across the Canadian Arctic. Using this program, subsistence harvesters can voluntarily provide specimens of salmon to document trends in abundances and distributions for all species. For detailed methods see Dunmall et al. (2013) and Dunmall (2018).

Reports of Pacific salmon harvested from 2013 to 2017 and provided to Fisheries and Oceans Canada through Arctic Salmon are summarized by species and compared to previous reports of salmon from 2000 to 2012 (Dunmall et al. 2013). Note that salmon abundance data are preliminary for 2017. Species identification was verified from actual specimens using keys of morphological and meristic counts (e.g., Scott and Crossman 1973).

Results

Pacific salmon are increasing in abundance and in geographic distribution in the Canadian Arctic. The number of salmon reported, the number of species of salmon harvested, and the geographic area of subsistence fisheries documenting salmon harvests all increased from 2013 to 2017.

Chum salmon (Oncorhynchus keta)
Chum salmon is consistently the most abundant Pacific salmon species harvested across the Canadian Arctic. It is also the only species with a long history and traditional knowledge of harvesting in the Mackenzie River (Dunmall et al. 2013). Moreover, at present chum salmon is the only salmon species that appears to have reproducing populations in the western Arctic (Dunmall 2018). Trends in chum salmon harvests include consistent low-level harvests in subsistence fisheries along the Mackenzie River, and occasional years of higher level harvests, called “exceptional years” (Fig. 1; Dunmall 2018). Two exceptional years occurred in 2016 and 2017, which contribute to an increasing trend in the frequency of these exceptional years. Also, the number of salmon that may be present during these exceptional years also appears to be increasing as the number of chum salmon provided during each of 2016 and 2017 doubled those provided in previous exceptional years, whereas numbers of chum salmon provided during the low-level harvest years remained consistent (Fig. 1).

Fig. 1. The number of each species of Pacific salmon traded in to the Arctic Salmon community-based monitoring program from harvesters across the Canadian Arctic from 2000–2017. Only one coho salmon was reported during this period (in 2011), thus it is not included.

Pink salmon (*Oncorhynchus gorbuscha*)

Higher pink salmon harvests occur in even-numbered years compared to odd-numbered years (Fig. 1). The number of pink salmon reported during both even and odd years, however, is increasing. Also, the geographic distribution of pink salmon harvests is increasing as they have now been reported in new locations, including Kugluktuk, Nunavut, and upstream in the Mackenzie River to Ft. Good Hope, Northwest Territories.

Sockeye salmon (*Oncorhynchus nerka*)

Sockeye salmon have experienced a rapid increase in reported harvests in the western Canadian Arctic in 2016 and 2017. Reported harvests increased from less than 10 per year from 2000 to 2015 to over 150 sockeye salmon reported in 2017 (Fig. 1). While several communities along the Mackenzie River reported higher sockeye harvests, the change was most pronounced in communities surrounding the Beaufort Sea. The geographic extent of sockeye salmon harvests also expanded eastward to now also include Cambridge Bay, Nunavut where two sockeye salmon were reported harvested in 2016 and one was reported in 2017.

Chinook (*Oncorhynchus tshawytscha*) and Coho salmon (*Oncorhynchus kisutch*)

The number of Chinook salmon reported increased in 2016 and 2017 compared to previous years, although the change was not as pronounced as it was for the other species of Pacific salmon (Fig. 1). Reported harvests increased from less than five per year from 2000 to 2015 to 10 in 2016 and 14 in 2017. No coho salmon were reported harvested in the Canadian Arctic from 2013 to 2017.
Conclusion

All species of Pacific salmon, with the exception of coho salmon, have rapidly increased in abundance and have expanded in geographic presence in the western Canadian Arctic since 2013, although the change is most pronounced in 2016 and 2017. While this increase may be due to an increase in reporting of harvested salmon by community harvesters, rather than an actual increase in the abundance of salmon themselves, the increase is consistent across almost all the communities in the western Canadian Arctic and for multiple species of salmon. Also, local knowledge suggests that more salmon have been present in the western Canadian Arctic in recent years. Therefore, the trends suggest that the occurrences and likely also the abundances of chum, pink, sockeye, and Chinook salmon are increasing in the Canadian Arctic, and at rates of increase not previously recorded.

The Arctic Salmon community-based monitoring program has also expanded in recent years. The geographic extent of the Arctic Salmon project now includes communities in Nunavut to facilitate the detection of Pacific salmon and Atlantic salmon in subsistence fisheries across the Canadian Arctic. The Arctic Salmon program has also shifted from monitoring salmon to monitoring the harvest of all “unusual fish” across the Canadian Arctic. These “unusual fish” include reports of all Pacific salmon species, Atlantic salmon, and also fish species that are native to the Arctic but are now found outside known distributions. This expansion is evidence of both the success of Arctic Salmon as a monitoring program among communities in the Canadian Arctic, and of the relevance of a community-based program for monitoring rare and potentially colonizing species across a vast and remote area.

Acknowledgments—We thank all participants of the Arctic Salmon community-based monitoring program, including harvesters, community organizations, government offices, and individuals, for providing samples and assisting in coordinating collections from across the Canadian Arctic. This research is only possible because of their contributions. We thank all organizations who provided funding support. We also thank the Alaska Department of Fish and Game Gene Conservation Laboratory for their efforts to confirm species identification for the sockeye salmon harvested in Nunavut. For more information on Arctic Salmon, please visit www.facebook.com/arcticsalmon.

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Global Warming Effect for Migration Route of Japanese Chum Salmon

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Keywords: Japanese chum salmon, global warming effect, migration route, COBE-SST, NOAA-NCEP Database

Introduction

Since the late 1990s, population size and survival of Japanese chum salmon (Oncorhynchus keta) have indicated a decreasing trend. Especially the population size of salmon returning to Hokkaido in 2016 and 2017, which were the minimum levels since 1990. However, it was predicted in the early 2000s that their population size in 2010 might become half of the maximum because of the new climate regime-shift since the end of the last century (Kaeriyama 2004, Kaeriyama et al. 2014). We also predicted the potential marine distribution of chum salmon in the North Pacific Ocean, the Bering Sea and the Chukchi Sea based on the SRES-A1B scenario in the Fourth Assessment Report of the IPCC (Kaeriyama 2008): 1) a northward shift in the distribution of chum salmon to the Chukchi Sea, and 2) loss of their migration route connecting Hokkaido with the Okhotsk Sea due to a thermal impediment.

Juvenile chum salmon remain in the coastal sea during the spring season (April–June) and migrate offshore at post-fingerling stage (average 10 cm, range 8–12 cm in fork length) in Japan. This offshore migration is usually preceded by larger individuals having the higher growth rate and forage more actively on prey than others (Kaeriyama 1986; Kaeriyama and Ueda 1998). Juvenile chum salmon originating from distant sources tended to grow faster than those from more proximal sources, likely contributing to larger body size in the former. Larger juvenile (>90 mm in fork length) tended to have higher growth rate than smaller fish (Honda et al. 2017). Namely, by the end of June, Japanese juvenile chum salmon will migrate from coastal seas around Japan to the Okhotsk Sea at the developmental stage of the post-fingerling.

The distribution of juvenile salmon along their migration trajectory may be affected by physiological conditions such as body size and environmental factors such as water temperature, ocean currents, food availability (zooplankton biomass), etc. (Urawa et al. 2016). Japanese juvenile chum salmon were previously distributed during summer and autumn periods (from the mid-July to the November) in the Okhotsk Sea (Ueno and Ishida 1998; Urawa 2015).

In the recent past, Chistyakova and Bugaev (2016) reported the distribution of juvenile pink and chum salmon with otolith marking released from hatcheries of Japan and Russia in the Okhotsk Sea in the fall (September–November) of 2011–2014. Juvenile chum salmon were distributed latitude 47–57°N and longitude 146–156°W, within their range. Their migration route was affected by the Okhotsk Sea Gyre. In July, in the Sea of Okhotsk coastal waters off South Sakhalin, the length and weight of most juvenile chum salmon of Japanese origin exceed 10 cm and 10 g (Shubin and Akinicheva 2016).

We addressed the potential progress of the global warming effects on Japanese chum salmon at the present moment in this paper.

Data and Methods

Sea surface temperature (SST) in the North Pacific Ocean, the Okhotsk Sea, the Bering Sea, and the Chukchi Sea was obtained via objective analysis using "COBE-SST" (Ishii et al. 2005) in the Japan Meteorological Agency (JMA) and the NOAA NCEP Database in the Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/data/timeeries/). To evaluate distribution area of chum salmon, we used their optimum temperature (8–12 °C) and adaptable temperature (5–12 °C) based on growth rate, feeding behavior and catch per unit effort (CPUE) as population density (Kaeriyama 2004). We analyzed scales of female adult chum salmon at age 4 returning to the Tsugaruishi River during 1996–2017 in order to evaluate the growth back-calculation.

Temporal change in return of Japanese chum salmon

Since the late 1990s, the population size of Japanese chum salmon showed decreasing trends. In the last 4 years, the population size did not link with the PDO despite the linkage between it and PDO in the other years (Fig.
1. The population size of Iwate chum salmon similarly showed decreasing trends since the late 1990s (Fig. 2a). Annual changes in anomalies of estimated fork lengths at the offshore migration and the age 1 generally synchronized with the population size except for 2013 and 2014 ocean entry years, the body size at the age 1 extremely decreased (Fig. 2b). The body size at the age 1 had a higher correlation with the population size than it at the offshore migration (Fig. 2c).

![Fig. 1. Temporal changes in population size of Japanese chum salmon and PDO (1965–2017).](image1)

![Fig. 2. Temporal changes in abundance (Fig. 2a), body size at the offshore migration and the age 1 for chum salmon in the Iwate Prefecture (Fig. 2b), and the relationship body size and return for chum salmon in the Iwate Prefecture.](image2)
Since the 1990s, the resident duration (days of adaptable temperature) of juvenile in the coast decreased through time, and the relationship between the resident duration and the survival of chum salmon in the Northern Japan Sea ($R^2 = 0.396^*$) and Sanriku ($R^2 = 0.256^*$) areas showed a significant positive correlation despite no correlation in the other areas (Fig. 3).

**Fig. 3.** Temporal changes in resident duration for juvenile chum salmon in coastal sea around Japan. OK: Okhotsk Sea Coast, EP: Eastern Pacific Coast, NJS: Northern Japan Sea Coast, SC: Sanriku Coast, SJS: Southern Japan Sea Coast.

*Japanese juvenile chum salmon have missed the migration route to the Okhotsk Sea since the 2010s*

Based on the COBE-SST database (Ishii et al. 2005) and Kaeriyama (2008), we evaluated the change in the area of adaptable temperature (AAT) for chum salmon in August of 2005 and 2017 in the North Pacific Ocean and the Okhotsk Sea (Fig. 4). The AAT in 2017 markedly decreased in the Okhotsk Sea and the Gulf of Alaska but increased in the Chukchi Sea. This indicates that the global warming will progress to affect the distribution area of chum salmon in the North Pacific Ocean.

**Fig. 4.** Changes in the area of adaptable temperature (AT) for chum salmon in August of 2005 (■) and 2017 (▲) in the North Pacific Ocean.
Figure 5 indicates the temporal change in areas of optimum and adaptable temperatures in July for juvenile chum salmon in the Okhotsk Sea. In the 2010s, the area of optimum temperature (AOT) has quietly departed from Hokkaido Island, even though the AOT was in touch with Hokkaido until the 2000s. The AOT in August gradually decreased and became less than half its size in the 2010s. The relationship between the SST of the southern Okhotsk Sea in July and the return rate (survival rate) of Hokkaido chum salmon has a significant positive correlation within the optimum temperature range (8–12.4 °C), but a negative correlation over the optimum temperature range (> 12.5 °C) (Fig. 6).

Since around 2013, the globally averaged SST has rapidly warmed up and reached its highest level on record. In the record-breaking warming, the contribution of the North Pacific region to the globally averaged SST anomaly has significantly increased and important effects from some processes at mid- and/or high latitudes are suggested (Urabe et al. 2017).

These results suggest that Hokkaido juvenile chum salmon would miss a migration route to the Okhotsk Sea, decrease their distribution area and their carrying capacity in summer, and decline their survival rate since the 2010s under the global warming effect in the Okhotsk Sea.
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Migration and Homing Behavior of Chum Salmon Tagged in the Okhotsk Sea, Eastern Hokkaido

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Keywords: archival tag, chum salmon, tagging, water temperature

Chum salmon (Oncorhynchus keta) is one of the most important species for commercial fisheries in Hokkaido in northern Japan. The Okhotsk coast in eastern Hokkaido is the principal area of salmon production in Japan. Commercial catches of chum salmon have been supported by intensive hatchery programs (Miyakoshi et al. 2013). In Hokkaido, returning chum salmon are fished in coastal waters mainly via set nets that are operated from September to December. Recently, coastal seawater temperatures in autumn have been higher than the historic mean. In years with high coastal seawater temperatures (≥ 20°C), it has been frequently observed that the peak timing of chum salmon landing was delayed and exploitation rates by coastal set net fisheries were low. In addition, high water temperatures might affect the distribution of chum salmon in coastal areas and the number of fish caught by each set net. In order to determine the effects of seawater temperature on commercial landings, the responses of migrating chum salmon to seawater temperature need to be elucidated.

To understand migration routes, depths, and temperatures experienced by returning chum salmon in the Okhotsk Sea, we caught chum salmon in the coastal waters, applied archival tags to them, and released them in early September 2016 and late August 2017. In this study, we report the outcomes of the tagging experiment for chum salmon in the Okhotsk Sea.

Fig. 1. Map of the sites where the fishing for chum salmon was conducted in the Okhotsk Sea in 2016 (○) and 2017 (●).

From 5–7 September 2016 and 28–30 August 2017, tagging experiments for chum salmon were conducted in the Okhotsk Sea from the research vessel Hokuyo maru (237 tons, Wakkanai Fisheries Research Institute, Hokkaido Research Organization). At a total of eight or nine sites in each year, we visually counted the number of chum salmon and fished for chum salmon at night (Fig. 1). At each site, fishing lights were used, and chum salmon that appeared were fished with a lure with raw bait (a slice of squid or Pacific saury) on the hook. The captured chum salmon were anesthetized, tagged with an archival tag on the base of the dorsal fin, and measured for fork length and...
weight. After recovery from anesthesia, the tagged fish were released into the sea. At the fishing sites, the vertical distributions of the seawater temperature and salinity were measured using CTD (Seabird SBE9plus, Sea-Bird Electronics, Inc., Bellevue, WA, USA).

After release, recaptures of tagged fish were reported by fishermen’s cooperative associations when the tagged fish were captured in commercial fisheries or by the Kitami Region Salmon Enhancement Program Association when the tagged fish were recaptured by the weirs that are installed in the rivers for broodstock collection.

In both 2016 and 2017, 14 chum salmon were tagged and released from the research vessel. In 2016, nine pink salmon also were tagged and released. Many chum salmon were counted and caught at sites west of the Kitami-Yamato Bank (approximately 80 km north of Cape Notoro) in both years and at sites northwest of the Kitami-Yamato Bank (approximately 90 km northeast of Cape Hinode) in 2017. At the sites where many chum salmon were counted or caught, the sea water temperatures were 15–18°C at the surface layer, 5–15°C at a depth of 15 m, and < 2°C at depths > 50 m.

Of the tagged chum salmon that were released, six and two fish were recaptured in 2016 and 2017, respectively, but no pink salmon were recaptured. In 2016, the tagged fish were recaptured from Shari to Esashi on the Okhotsk coast. The elapsed days from the release were three to 13 days. In 2017, the fish were recaptured in Shari. The elapsed days from the release were nine and 21 days, respectively. Thus, all of the tagged fish were recaptured on the Okhotsk coast.

Some of the tagged fish migrated diurnally between the surface layer and a depth of 200 m. During daylight hours the tagged fish preferred sea water temperatures of 1°C at a depth of 200 m. It is considered to regulate their cavity temperature (Azumaya and Ishida 2005). Our study suggests that seawater temperatures are affecting salmon behavior in the coastal areas.

In the Okhotsk Sea off the coast of the Shiretoko Peninsula and Abashiri region, biotelemetry studies were conducted on chum salmon in the 1980s (Soeda et al. 1985; 1987; Shimamura et al. 1987; Yoza et al. 1985). In their papers, many findings on the migratory behavior of chum salmon were reported. We observed many migratory behaviors of chum salmon in our study that were similar to the findings of previous studies. Because the seawater temperatures around Hokkaido in autumn have been higher in recent years, the monitoring of chum salmon behavior relative to climate change is important.

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Environmental Variability and Chum Salmon Production at the Northwestern Pacific Ocean

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Keywords: chum salmon, North Pacific, Korean waters, climate change, Pacific Decadal Oscillation (PDO)

Introduction
Chum salmon have the widest distribution range among Pacific salmon species, but the main populations occupy the northwestern Pacific Ocean. Spawning rivers of Asian chum salmon are spread over Russian, Japanese, and Korean territories, and the middle part of the eastern Korean Peninsula is the southern limit of the chum salmon distribution (Fig. 1a).

Events of decadal-scale climate change, frequently called the climate regime shift and expressed by the index known as Pacific Decadal Oscillation (PDO), were reported in the mid-1940s and the mid-1970s in the North Pacific (Fig. 1b), and the changing patterns in the catches of pink salmon matched well with that of climate regime shifts through the 20th century (Francis and Hare 1994; Hare and Manton 2000). In general, a positive anomaly of the PDO index tends to reflect a warm environment in the eastern and northern Pacific, while a positive anomaly reflects a cool environment in the central and western Pacific (Fig. 1c and d).

In this paper, we investigate the relationship between climate and environmental variability, enhancement program, and chum salmon production in the northwestern Pacific Ocean. Our special interests are also focused on controlling factors that determine the return rate of chum salmon in Korean waters. Results of our analysis may be helpful in enhancing ecological knowledge and improving fishery management under changing climate conditions.

Materials and Methods
To investigate the relationship between survival of chum salmon and environmental conditions, the large-scale climate indices PDO (http://jisao.washington.edu/pdo/PDO.latest) were used in this paper, during the 1925-2014 period. For the habitat environment of salmon fry in Korean waters, two sources of seawater temperatures were available. One is survey data from the National Institute of Fisheries Science (NIFS, formerly known as the National Fisheries Research and Development Institute) and another data is seawater temperature that was measured at the Sokcho Light House which is located the nearest to the releasing point of chum salmon fry during the springtime (Fig. 1a). Offspring from a single spawning year return to their natal streams within 2 to 5 years, and age 6 and older are very few (Seo et al. 2006), so that we considered only age 2 through to 5 for the calculation of chum salmon return rate. The summation of different returns divided by total release is the return rate of chum salmon in a specific year. The formula used for this calculation is

\[ R_i = \frac{(age2_\_p \times c_{i+1}) + (age3_\_p \times c_{i+3}) + (age4_\_p \times c_{i+4}) + (age5_\_p \times c_{i+5})}{release_i} \]

where \( R_i \) is the return rate of chum salmon released in year \( i \), release \( i \) is the number of fry released in year \( i \), \( c_{i+1} \) is the number of chum salmon returning to a natal river in year \( i+1 \), and age \( 2_\_p \) is the proportion of Age-2 salmon, etc.

To detect long-term trends or climate and ecosystem regime shifts visually, we used the Cumulative Summation (CuSum). The Sequential Regime Shift Detector (SRSD) developed by Rodionov (2005) was used to detect the discontinuities in time series. Cross-Correlation Function (CCF) analysis was used to examine the lagged relationship between climatic/ environmental factors and chum salmon catches.

Results
The characteristics of environmental variability were examined by the changing pattern of seawater temperature which varies geographically and temporally at each habitat region of chum salmon in the northwestern Pacific. The Okhotsk Sea and the Bering Sea which are the main residence areas of immature chum salmon did not
demonstrate the same temperature pattern as the western North Pacific in Korean and Japanese waters (Fig. 1c and d).

Fig. 1. Study area and environmental variability used in this study. (a) Seawater temperatures were collected from the ocean monitoring area (shaded) and the Sokcho Lighthouse (white dot) in Korean waters, (b) monthly values of the Pacific Decadal Oscillation Index, 1900–2009. Red line indicates 10-year moving average. (c) average sea surface temperature anomalies during negative PDO, May 1998–August 2002, and (d) average sea surface temperature anomalies during positive PDO, September 2002–September 2007 (McKinnell et al. 2010).
Fig. 2. Relationship between environmental variability and chum salmon catch. (a) Trend of Cumulative Summation (CuSum) of regional chum salmon catches (thin lines) and Pacific Decadal Oscillation indices (dotted lines) during 1925–2012, and (b) Cross-Correlation Function (CCF) analysis on Pacific Decadal Oscillation index and chum salmon catches.

The CuSum plots on the time-series PDO index revealed the big changes happened in the mid-1940s and 1970s, with a relatively small change in the late 1990s, showing that the 1976/77 climate regime shift was one of the strongest events in the 20th century (Fig. 2a). The CuSum curve for Russian chum salmon catch revealed a turning point in the late 1980s after one to two decades of climate regime shift in the 1970s. A similar relationship was
found in an earlier period during the 1940s through to the 1950s. The CuSum curve from Japanese chum salmon, however, indicated a turning point in the late 1970s right after the turning point of the PDO in mid-1970s, although no matched turning points in catch and PDO were found in the 1940s and 1990s. For Korean stock, due to the lack of longer catch statistics, we could not see any relationship between climate index and catch. Each regional stock in the western Pacific showed a different correlation on chum salmon catch and PDO. The CCF analysis indicated that significant negative correlations between PDO and Russian stock were found with a time-lag of 0 and 1 year. For Japanese stock, however, correlations were positive for 6 years, and statistical significances were found in the time-lag of 0 through 2 years. Korean stock also showed positive correlations with time like the Japanese one, but there was no statistical significance through 6 years (Fig. 2b). As shown in Figures 3c and 3d, it has been frequently observed that seawater temperatures in northern (i.e., off the Kamchatka Peninsula of Russian waters) and southern (i.e., Japanese and Korean waters) waters were opposite, which indicates that low seawater temperature at juvenile habitats are beneficial to chum salmon production with a time-lag of 0-1 years.

![Graph](image)

**Fig. 3.** Time-series of (a) Return rate (% dot) of chum salmon released from Yangyang hatchery and mean seawater temperature anomalies in April–May (line), and (b) Mean seawater temperature anomalies (bar) and the number of days (line) exceeding 14℃ in daily mean at Sokcho Lighthouse in April–May.

The return rates of Korean chum salmon released from the Yangyang hatchery in a specific year were generally low ranging from 0.1% to 0.5% (Fig. 3a). The new estimation of return rate for Korean chum salmon was slightly lower than a former estimation which was based on the assumption of Age-4 return, although they showed
similar trends ($r = 0.716, p < 0.01$). A return rate of Korean chum salmon seemed to be linked with the seawater temperature of coastal waters during their first year of ocean life. Though the general trend seems to be parallel during the mid-1980s to mid-1990s, the statistical analysis on the seawater temperature at the lighthouse during April and May and the return rate of chum salmon released in a specific year indicates a significant $r$ value ($r = -0.492^*$) at the 0.05 level. Coastal temperature observation at Sokcho Light House indicated that the largest negative anomalies that occurred in the early-mid 1980s matched with the high return rate of chum salmon. As the average lighthouse seawater temperature in April through May showed, lighthouse seawater temperature in April also showed a significant correlation ($r = -0.486, p < 0.05$) with return rate. Also, the high numbers in days exceeding $14^\circ C$ in April and May appeared mostly in the 1990s through to the 2000s (Fig. 3b), which means that warm ocean temperature may cause the high mortality of chum salmon fry in coastal areas. Although there was no statistical significance in the 5% level between return rate and SST observation in ocean monitoring stations or the number of days exceeding $14^\circ C$, correlations were relatively high. Due to the lack of data collection, we cannot estimate the return rate during the 1998–2004 period.

REFERENCES


An Evaluation of the Influence of Stock Abundance and Global Temperature Anomaly on Pacific Salmon Body Weight in the North Pacific Ocean

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Keywords: Pacific salmon, average body weight, stock abundance, global temperature anomaly

The objective of this study is an evaluation of the relationships between Pacific salmon stock abundance, water temperature anomalies, and Pacific salmon body weight to determine a main salmon growth driving factor during their marine phase. Relationships between Pacific salmon catch values (1961–2015) as a stock abundance index, the Northern Hemisphere Land and Sea Surface Temperature Anomaly Index (N.HEMI+dSST), and salmon body weight in commercial catches of the North Pacific countries (Table 1) were assessed using stepwise multiple regression analysis. The temperature anomaly index values are calculated in correspondence with the marine phase duration of Pacific salmon species: two-year averaging is used for pink and coho salmon, four-year averaging is used for chum, sockeye, and Chinook (Bugaev 2017).

Table 1. Long-term average body weight (kg) of Pacific salmon in commercial catches, 1961–2015.

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pink</td>
<td>1.34 (1.10–1.62)</td>
<td>1.26 (0.94–1.79)</td>
<td>1.61 (1.23–2.22)</td>
<td>2.10 (1.37–2.96)</td>
<td>1.86 (1.39–2.98)</td>
</tr>
<tr>
<td>Chum</td>
<td>3.48 (2.80–4.05)</td>
<td>2.96 (2.12–3.76)</td>
<td>3.61 (3.07–4.13)</td>
<td>4.52 (3.48–5.22)</td>
<td>5.22 (4.34–6.26)</td>
</tr>
<tr>
<td>Sockeye</td>
<td>2.74 (2.29–3.30)</td>
<td>2.07 (1.48–3.00)</td>
<td>2.71 (2.16–3.39)</td>
<td>2.60 (1.54–2.99)</td>
<td>2.78 (2.21–3.37)</td>
</tr>
<tr>
<td>Coho</td>
<td>3.14 (2.50–3.76)</td>
<td>2.53 (1.72–4.00)</td>
<td>3.41 (2.81–4.01)</td>
<td>3.20 (2.05–4.91)</td>
<td>3.29 (2.48–4.09)</td>
</tr>
<tr>
<td>Chinook</td>
<td>8.20 (4.70–11.01)</td>
<td>4.87 (3.52–10.00)</td>
<td>7.83 (5.52–9.26)</td>
<td>6.17 (3.59–10.39)</td>
<td>6.82 (5.41–9.12)</td>
</tr>
</tbody>
</table>

Pacific salmon catches by the NPAFC member countries reached historic high levels at the end of the first decade of the current century (see https://npafc.org/statistics/). Then, in odd years, overall commercial salmon fishery harvest fell about 20% from levels of 607 or 608 million fish to 507 million fish in 2015. In even years, Pacific salmon catches follow the same trend with the historical record, in 2012, 464 million fish were caught and catches decreased to 389 million fish in 2014.
Interannual dynamics of the N.HEMI+dSST index from 1925–2015 reveals a pronounced increasing trend over the last 25 years, since the mid-1980s (Fig. 1). The periodogram obtained by means of Fourier spectral analysis supposes an existence of one distinct irregular cycle besides unapparent spectral extremum related to double (22-year) solar cycle (Fig. 2).

Most of the salmon body weight data series show a negative trend that reflects an overall tendency towards a lowering of captured salmon body weight (Fig. 3). Data of Japanese fisheries remain an exception due to the significant contribution of the driftnet fishery to the total commercial salmon catch by Japan. This data is excluded from the further analysis.

Russia—Estimated multiple regression coefficients (R) are the highest for chum (0.75) and Chinook (0.86) salmon (Table 2). The regression weight of the temperature anomaly ($b_2$) is higher for both salmon species: -0.506 for chum and -0.966 for Chinook (Table 3). Regression weight of stock abundance is also relatively high: -0.281 for chum and -0.348 for Chinook (Table 3). Regression weight of stock abundance is also relatively high: -0.281 and -0.348, accordingly. As for pink, sockeye, and coho salmon, regression coefficients statistically vary between weak and moderate and are rather similar ($R = 0.38–0.44$). Pink salmon body weight demonstrates a negative relationship with stock abundance index ($b_1 = -0.619$) but a positive relationship with N.HEMI+dSST ($b_2 = 0.465$). Restricting the analysis by the northern group of pink salmon stocks only (Chukotka, Kamchatka, and mainland Sea of Okhotsk coast), salmon body weight has a moderate relationship with the explanatory variables ($R = 0.69$). While the weight of both variables is close, the regression sign remains opposite: $b_1 = -0.738$ and $b_2 = 0.713$. It can be supposed that a negative impact of increasing stock abundance on pink salmon growth is compensated by the positive effect of surface layer warming in the North Pacific Ocean (Radchenko et al. 2018).
Table 2. Results of multiple regression modelling of average Pacific salmon body weight relationship with their commercial catches (1,000 fish) and annual values of the N.HEMI+dSST index, 1961–2015.

<table>
<thead>
<tr>
<th>Salmon species</th>
<th>Regions</th>
<th>Russia</th>
<th>USA (Alaska)</th>
<th>USA (WOC)</th>
<th>Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R$</td>
<td>$p$</td>
<td>$R$</td>
<td>$p$</td>
<td>$R$</td>
</tr>
<tr>
<td>Pink</td>
<td>0.44</td>
<td>$&lt;0.01$</td>
<td><strong>0.62</strong></td>
<td>$&lt;0.001$</td>
<td><strong>0.83</strong></td>
</tr>
<tr>
<td>Chum</td>
<td><strong>0.75</strong></td>
<td>$&lt;0.001$</td>
<td>0.20</td>
<td>0.348</td>
<td><strong>0.62</strong></td>
</tr>
<tr>
<td>Sockeye</td>
<td>0.38</td>
<td>$&lt;0.05$</td>
<td>0.35</td>
<td>$&lt;0.05$</td>
<td>0.33</td>
</tr>
<tr>
<td>Coho</td>
<td>0.43</td>
<td>$&lt;0.01$</td>
<td><strong>0.57</strong></td>
<td>$&lt;0.001$</td>
<td>0.13</td>
</tr>
<tr>
<td>Chinook</td>
<td><strong>0.86</strong></td>
<td>$&lt;0.001$</td>
<td><strong>0.81</strong></td>
<td>$&lt;0.001$</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Remarks: $R$—coefficient of multiple regression, $p$—confidence probability

Table 3. Standardized coefficient (beta) estimated to test how well the independent variables (commercial catches and the N.HEMI+dSST index) relate to average Pacific salmon body weight, 1961–2015.

<table>
<thead>
<tr>
<th>Salmon species</th>
<th>Regions: $b_1$ (Catch)</th>
<th>$beta$</th>
<th>$SE$</th>
<th>$beta$</th>
<th>$SE$</th>
<th>$beta$</th>
<th>$SE$</th>
<th>$beta$</th>
<th>$SE$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pink</td>
<td>$-0.619$</td>
<td>0.178</td>
<td>-0.796</td>
<td>0.180</td>
<td>-0.129</td>
<td>0.112</td>
<td>-0.121</td>
<td>0.135</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.465$</td>
<td>0.178</td>
<td>0.247</td>
<td>0.180</td>
<td>-0.834</td>
<td>0.112</td>
<td>-0.444</td>
<td>0.135</td>
<td></td>
</tr>
<tr>
<td>Chum</td>
<td>$-0.281$</td>
<td>0.147</td>
<td>0.344</td>
<td>0.236</td>
<td>-0.249</td>
<td>0.188</td>
<td>-0.255</td>
<td>0.109</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$-0.506$</td>
<td>0.147</td>
<td>-0.302</td>
<td>0.236</td>
<td>-0.404</td>
<td>0.188</td>
<td>-0.648</td>
<td>0.109</td>
<td></td>
</tr>
<tr>
<td>Sockeye</td>
<td>$-0.343$</td>
<td>0.296</td>
<td>-0.338</td>
<td>0.163</td>
<td>-0.004</td>
<td>0.168</td>
<td>0.033</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$-0.039$</td>
<td>0.296</td>
<td>-0.015</td>
<td>0.163</td>
<td>-0.336</td>
<td>0.168</td>
<td>-0.678</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>Coho</td>
<td>$-0.216$</td>
<td>0.132</td>
<td>0.029</td>
<td>0.131</td>
<td>0.060</td>
<td>0.222</td>
<td>-0.649</td>
<td>0.238</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$-0.310$</td>
<td>0.132</td>
<td>-0.587</td>
<td>0.131</td>
<td>0.168</td>
<td>0.222</td>
<td>-0.491</td>
<td>0.238</td>
<td></td>
</tr>
<tr>
<td>Chinook</td>
<td>$-0.348$</td>
<td>0.080</td>
<td>0.399</td>
<td>0.089</td>
<td>-0.217</td>
<td>0.167</td>
<td>-1.054</td>
<td>0.257</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$-0.966$</td>
<td>0.080</td>
<td>-0.561</td>
<td>0.089</td>
<td>-0.189</td>
<td>0.167</td>
<td>-0.691</td>
<td>0.257</td>
<td></td>
</tr>
</tbody>
</table>

Remarks: $b_1$, $b_2$—standardized regression coefficients, $SE$—standard error

USA (Alaska)—For the Alaskan salmon, estimated multiple regression coefficients ($R$) are the highest for Chinook ($0.81$), pink ($0.62$), and coho salmon ($0.57$). The regression weight of the temperature anomaly is higher for Chinook and coho: $b_2 = -0.561$ and $-0.587$, accordingly, while stock abundance factor is more significant for pink salmon: $b_1 = -0.796$. Both factors negatively impact salmon weight growth.

USA (Washington, Oregon, California, or WOC)—Correlations are weak and regression coefficients are very low for two the most important salmon species of this region, coho ($R = 0.12$) and Chinook ($R = 0.19$). It may be related to a high hatchery fish contribution into their total stock abundance. The highest regression coefficients are computed for pink ($R = 0.83$) and chum ($R = 0.62$) salmon. The regression weight of the temperature anomaly was higher for both species: $b_2 = -0.834$ and $-0.404$, correspondingly. For sockeye, the correlation is weak ($R = 0.33$) and the increasing temperature anomaly also increases the impacts for pink and chum salmon, $b_2 = -0.336$.

Canada—Among the Pacific Rim countries, Canada releases large amounts of fish from hatching facilities and spawning channels. Hatchery fish compose about 70% of sockeye, and 15–20% of coho and Chinook populations in the last years. However, both predictors negatively impact weight growth of Canadian salmon. The highest multiple regression coefficients are obtained for sockeye ($R = 0.69$) and chum ($R = 0.63$) salmon. The regression weight of the temperature anomaly was higher than the weight of abundance index for planktivorous salmon species; $b_2 = -0.444$ for pink, $-0.648$ for chum, and $-0.678$ for sockeye. For “predatory” salmon species, the
regression weight of stock abundance was notably higher: $b_1 = -0.649$, $b_2 = -0.491$ for coho and $b_1 = -1.054$, $b_2 = -0.691$ for Chinook. In ~ 85% of cases, a complex interrelation is observed between average body weight and “stock abundance + global temperature anomaly” indices. The correlation coefficient $R$ is $<0.3$ in 15%, $>0.3 \leq 0.6$ in 45%, and $>0.6$ in 40% of the cases examined.

In conclusion, the N.HEMI+dSST index is the most significant factor in about 70% of the multiple regressions under consideration. A negative impact of the increasing temperature anomaly is more significant in the southernmost of the studied regions, in the USA (WOC) and Canada. This is quite understandable since the negative effect of temperature increases on Pacific salmon becomes evident primarily near the southern borders of their areas.

For most of the Pacific salmon stocks, there are different changing long-term trends in Pacific salmon body weight dynamics and no universal relationships are evident; for example, pink salmon body weight in Russian commercial catches had a negative trend till the mid-1980s, which was later replaced by a considerably unstable positive trend. These short-term trends are determined by multivariable interactions of environmental factors and their variable influence on salmon growth at different life stages. The periodicity of a trend breaks should be taken into account when considering regulations of Pacific salmon size and weight dynamics over a long period of time.

REFERENCES


Return of Chum Salmon and Water Quality and Ecology in the Rivers Connected with the Eastern Coast of Korea

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¹Department of Marine Bioscience, Gangneun-Wonju National University, Gangwon, Korea
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³Inland Life Resources Center, Korea Fisheries Resources Agency, Gangwon, Korea

Keywords: returning rate, river condition, trophic level

Chum salmon, Oncorhynchus keta, is major species which returns to rivers in Korea, and about 98% of chum salmon return to rivers along the eastern coast of Korea. The returning rate of chum salmon in Korea is generally proportional to latitude, release amount, water quality, and ecological status in rivers which are important factors affecting the return of the species to the rivers. In this study, water quality and biological characteristics were monitored in five rivers along the eastern coast of Korea from the Taehwa River, the southernmost river to the Myeongpa River, the northernmost river.

![Fig. 1. The major natal rivers of chum salmon in Korea.](image)

**Table 1.** The velocity and discharge rates for each river.

<table>
<thead>
<tr>
<th></th>
<th>Meongpa</th>
<th>Bukchon</th>
<th>Namdaecheon</th>
<th>Yeongok</th>
<th>Taehwa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>1.16</td>
<td>0.35</td>
<td>0.24</td>
<td>0.21</td>
<td>0.049</td>
</tr>
<tr>
<td>Discharge (m³/s)</td>
<td>2.59</td>
<td>9.09</td>
<td>21.15</td>
<td>5.18</td>
<td>5.96</td>
</tr>
</tbody>
</table>

**Table 2.** The water temperature, salinity, and dissolved oxygen of each river in June and August 2017.

<table>
<thead>
<tr>
<th></th>
<th>Meongpa</th>
<th>Bukchon</th>
<th>Namdaecheon</th>
<th>Yeongok</th>
<th>Taehwa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tem. (°C)</td>
<td>18.57</td>
<td>20.34</td>
<td>21.8</td>
<td>24.36</td>
<td>25.67</td>
</tr>
<tr>
<td>Sal. (psu)</td>
<td>0.05</td>
<td>0.05</td>
<td>1.4</td>
<td>2.17</td>
<td>3.3</td>
</tr>
<tr>
<td>Do. (ml/l)</td>
<td>6.97</td>
<td>7.15</td>
<td>7.17</td>
<td>7.96</td>
<td>7.79</td>
</tr>
</tbody>
</table>

The five rivers (i.e., the Taehwa, Yeongok, Namdaecheon, Bukchon, and Myeongpa from south to north of the eastern coast) (Fig. 1), have distinctly different environmental conditions. The latter four rivers are surrounded by natural forests, but the Taehwa River flows through a large industrial and urban area before it reaches the sea. Thus, it is assumed that the Taehwa River has poor water quality due to human-induced influences, while water quality in the other rivers are improved with the latitude and geographical features. The water temperature and dissolved oxygen (DO) have decreased with increasing latitude (Table 1). DO in each river has a range from 6.97 to...
7.96 (Table 1), and the highest value was recorded in Teahwa and Yeongok (Table 2). The highest water flow such as velocity and discharge was recorded in the Namdaecheon (21.2 m³/s) (Table 2). In the results of the stable isotope analysis, δ¹³C values of suspended particulate organic matter (SPOM) were about -30‰ in all sampling sites, suggesting a higher contribution of terrestrial organic matter. For δ¹⁵N values, SPOM were generally higher in August than those in June (Fig. 2). The consumers in Myoungpa, Buk, and Yeongok streams showed wide ranges in δ¹³C values (-28.0‰ to -19.6‰ in June; -29.3‰ to -22.0‰ in August), suggesting a higher contribution of both terrestrial- and marine-derived organic matter (Fig. 2). In contrast, the consumers in Namdae stream showed a relatively narrow range in δ¹³C values (-24.0‰ to -18.0‰ in June; -26.5‰ to -22.1‰ in August) compared with other streams, suggesting an important contribution of benthic production and/or marine-derived organic matter (Fig. 2). At all sites, most consumers in August had narrower and more depleted δ¹³C ranges compared to those in June, suggesting an increased contribution of terrestrial-derived organic matter due to the summer monsoon effect created by heavy rainfall (Fig. 2). The δ¹⁵N values for most consumers have shown wide ranges at all sites during both periods, suggesting that there was a stepwise trophic enrichment in δ¹⁵N with increasing trophic level from invertebrate to fish consumers (Fig. 3).

**Fig. 2.** δ¹³C and δ¹⁵N values of suspended particulate organic matter (SPOM) sampled at the five stations during June and August 2017.

**Fig. 3.** Bi-plots of the δ¹³C and δ¹⁵N values for consumers (circles) at the sampling sites during two periods (June and August 2017). Isotopic niche areas of consumers at the sites during the periods, estimated as the total area (TA, dotted line) and standard ellipse area (SEAc, solid line).
Among the rivers studied, Namdaecheon, the major releasing and returning area for chum salmon has relatively good status, especially with regards to biological condition (i.e., prey, predator, competition species) when compared with the other rivers. Whereas in the Taehwa River, prey competition for chum salmon with animals that belong to the same trophic level seems to be relatively strong; consequently, prey selection of chum salmon may be restricted. The results from this study will contribute to future research, which seeks to determine the best habitat for returning chum salmon, and better predict the release/survival mechanisms of juvenile salmon in Korean river systems.
Teaming up Internationally to Optimize Wild and Hatchery Pacific Salmon Production in a Future of Changing Ocean Ecosystems—the International Year of the Salmon (IYS)

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Introduction

I like to say that we know a lot about Pacific salmon, but what we need to know most, we mostly do not know. This means that we mostly are not able to forecast the abundances of returning adult Pacific salmon. Pacific salmon catches are at historic high levels, however there is no understanding of why the abundances continue to be so high or how long the high abundances will last. We are not able to make consistently reliable forecasts because we do not understand the basic mechanisms that regulate the population dynamics of Pacific salmon. In particular, we do not understand how climate and a changing ocean ecosystem will affect salmon abundances. In the past, we believed that adult abundances were most closely related to the number of smolts that entered the ocean. It was only a little over 20 years ago that we started to discover that ocean ecosystems profoundly affected production with impacts that were not random. We now realize that greenhouse gas induced changes in climate in the immediate future will alter ocean ecosystems, adding to the complexity of forecasting without an understanding of the mechanisms regulating survival in the ocean.

It is important that the problem of forecasting Pacific salmon production be related to hatchery as well as to wild Pacific salmon. Understanding the factors affecting the ocean survival of hatchery fish often receives less attention and some consider that hatchery fish are inherent in the mechanisms that regulate wild salmon survival in the ocean. Recent estimates are that about 40% of the biomass of all Pacific salmon in the ocean originates from hatcheries (Ruggerone and Irvine, 2018). As abundances of all Pacific salmon are at historic high levels (Ruggerone and Irvine, 2018) and the number of hatchery fish released into the ocean has not changed much since the late 1980s (data from NPAFC Pacific salmonid hatchery release statistics, updated 31 July 2018), it appears that hatchery fish are almost of equal importance to wild salmon when looking into the future of Pacific salmon production. Thus, it is the purpose of my presentation to focus attention on the need to identify the mechanisms that regulate the abundances of wild and hatchery Pacific salmon. I am suggesting that this can best be done by establishing international teams of researchers. The International Year of the Salmon can be the opportunity to establish these teams.

Why international cooperation is urgent

Most of us are familiar with the anomalous warming that occurred late in 2013 in the eastern Pacific and combined with the El Niño of 2014–2016, produced some of the warmest ocean temperatures on record over an area from Alaska to Mexico (Fig. 1). Recently published research (Wang et al. 2018) shows that the warming event of 2013–2014, often referred to as the “blob” may be related to sea ice loss in the Arctic and thus could become more common. There is considerable evidence that the warming of 2013–2014 reduced nutrient levels, resulting in poor production of Pacific salmon in a number of areas. Thus, there is an urgency in understanding how population size is determined in the ocean so that the impacts of these and other extreme climate/ocean events on wild and hatchery salmon are understood in advance of adult returns. In the past, finding out why population trends and synchronies occurred would have been nice to know, but this understanding is now urgently needed.

I will begin by providing examples of production trends to show that the problem of understanding the mechanisms regulating Pacific salmon production is best dealt with as an international problem. Next, I want to show that the production of hatchery fish needs to be re-evaluated to be able to adapt to the expected ocean ecosystem changes. I propose that adapting hatchery production to a future of changing ocean ecosystems is also an international problem. In my third topic, I will speculate on a mechanism that may be fundamental to both hatchery and wild production. I conclude with comments on why the International Year of the Salmon can be the beginning of international teamwork that will ensure that each country has the information to make management decisions that optimize economic opportunities for hatchery and wild-based fisheries. We cooperate internationally to solve complex human medical issues and we now need to use the same kind of cooperation to ensure that the future...
stewardship of Pacific salmon anticipates the impacts of ocean changes rather than being continually surprised by unexpected adult returns.

![Image of sea surface temperature anomalies](http://polar.ncep.noaa.gov/sst/ophi/)

**Fig. 1.** North Pacific sea surface temperature anomalies from July 2014 to December 2017, data from http://polar.ncep.noaa.gov/sst/ophi/

1—Why understanding the mechanisms that regulate the abundance of Pacific salmon is an international problem

There is a history of increasing and decreasing trends in the production of Pacific salmon. I will briefly describe a few of these trends as examples of the economic consequences of our inability to understand what is causing the trends. I am using these examples later in my presentation to hypothesize that there could be a common mechanism involved in all trends that is related to metabolic processes in the early marine period.

*North Pacific commercial catches of chum salmon*

![Graph of North Pacific commercial catch of chum salmon by country](http://example.com/graph)

**Fig. 2.** North Pacific commercial catch of chum salmon by country. Data from North Pacific salmonid catch statistics (updated 31 July 2018). North Pacific Anadromous Fish Commission, Vancouver (Available: www.npafc.org).

There is a declining trend in the commercial catch of chum salmon by Japan that started about 2006 and continued through to 2017 (Fig. 2). The decline occurred despite an almost constant hatchery release of hatchery fish (from 1990 to 2016 the average hatchery release by Japan was about 2.0 billion fish and during the period of
decline the average was 1.9 billion). Beginning at almost the same time of the declining trend, there has been an increasing trend in the catch of chum salmon from Russia (Fig. 2). Of relevance to an explanation for the declining trend of Japanese production is the knowledge that the juvenile chum salmon from Japan and Russia rear in the Sea of Okhotsk before migrating into the open North Pacific (Urawa et al. 2018). In a recent paper by Shuntov et al. (2018), the authors estimate that prey for juvenile Pacific salmon in the Sea of Okhotsk is not limiting the production of Pacific salmon, suggesting that the factors responsible for the declining trend of Japanese chum salmon are initiated before they enter the Sea of Okhotsk.

**Commercial catches of chum salmon in Alaska**

The commercial catch of chum salmon in Alaska increased in 1980 and again in the early 1990s with a record catch in 2017 (Fig. 3). Hatchery and wild catch estimates are available for Southeast Alaska showing that the major increase in catch is from hatchery fish (Fig. 4). However, as the increased catch occurred, there was an unexplained small decreasing trend in the wild chum catch. One possible explanation is that there is competition between the hatchery and wild fish with the more numerous hatchery juveniles reducing the availability of prey for the wild fish resulting in more energy used by wild fish to find food and less energy available for somatic growth or lipid storage for the winter. Another explanation could be that the releases of hatchery fish are better matched to periods of maximum prey production and benefit from being in the right place at the right time.

**Commercial catch of pink salmon in the North Pacific**

![Fig. 3. Commercial chum salmon catch in Alaska. Data from North Pacific salmonid catch statistics (updated 31 July 2018). North Pacific Anadromous Fish Commission, Vancouver (Available: www.npafc.org).](image1)

![Fig. 4. Hatchery and wild composition of the commercial chum salmon catch in Alaska.](image2)

![Fig. 5. North Pacific commercial catch of pink salmon by country. Data from North Pacific salmonid catch statistics (updated 31 July 2018). North Pacific Anadromous Fish Commission, Vancouver (Available: www.npafc.org).](image3)
The commercial catch of pink salmon by all countries increased since 1970 and was 449,067 metric tons in 2017 (data from NPAFC Pacific salmonid catch statistics, updated 31 July 2018). From 1970 to 1999, the catch trends of odd- and even-year pink salmon were similar, with the odd-year catches always exceeding the previous even-year catches (Fig. 5). Beginning in 2000, the catch trends of the two brood years changed, with the odd-year catches increasing at a much faster rate than the even-year catches. The increase was not a result of hatchery production as there was a 4% increase in the hatchery production in average even-year releases beginning in 2000. Accordingly, the odd-year fish must be experiencing improved production compared to the even-brood year. In a study by Wechter et al. (2017), the authors measured insulin-like growth factor, IGF-1 (Beckman et al. 2004) and energy densities of even- and odd-year juveniles in the northeastern Bering Sea. They observed differences in how the two brood years grew and stored energy in the first ocean year. They concluded that there was evidence that later in the first ocean year the even-year populations allocate more energy to lipid storage than to somatic growth than the odd-year populations. The even-year fish that stored more lipid for use in the winter, would be smaller and may have less appetite for growing in the winter as discussed for other species by (Biro et al. 2004). In contrast, the odd-year fish would be larger at the beginning of winter and would continue to feed and grow in the winter if prey were abundant. Importantly, this study produced one of the few publications that researched the mechanisms causing trends in production as the behaviour and response of the odd- and even-year pink salmon is a clue to the explaining the more general mechanisms that regulate growth and ocean survival of all Pacific salmon.

Commercial catches of Chinook salmon

Chinook salmon are mostly caught in North America. The total catches by all countries from 2000 to 2017 averaged 9,969 metric tons with 93% caught in North America (data from NPAFC Pacific salmonid catch statistics, updated 31 July 2018). Despite the very small catches, Chinook salmon are an iconic species in North America, because of their large size, value in the recreational fishery and cultural significance. The Commercial catches of Chinook salmon by all countries began to decline in the early 1980s (Fig. 6). Some of this decline related to regulation changes (Riddell et al. 2018), but the decline is mostly related to reduced productivity (Riddell et al. 2018). In recent years the declining trend in abundance off North America has become alarming as negotiators found out in the renegotiation of the Pacific salmon treaty between Canada and The United States. In British Columbia, the declining abundances are thought to be related to declining production of a group of iconic Killer Whales resulting in recent reductions in exploitation rates and area closures for the recreational fishery. An example of the declining trends in production is in the return of Chinook salmon to the Taku River that flows from British Columbia, Canada through Alaska and into the Gulf of Alaska at Juneau (Fig. 7). The data include estimates of harvest which are believed to have low exploitation rates of about 10 to 20%. The point is that there is an unexplained declining trend and there are numerous trends like this from Alaska to California. Because the trends are basin scale, it is most likely that there is a common mechanism. A common mechanism such as reduced early marine growth could be exacerbated by other sources of mortality on larger individuals if these larger fish become less able to avoid predation.
Total returns of sockeye salmon to the Fraser River in British Columbia

Sockeye salmon from the Fraser River in British Columbia produce what is probably the most important fishery on Canada’s Pacific coast. The returning adult fish migrate into waters within the United States requiring the need for a management treaty between the two countries. The resulting Pacific Salmon Commission had its first meeting in 1937. The total returns are complicated by cycles that are almost consistently four years with one dominant run every fourth year (Fig. 8). There is a clear increasing trend in the total returns from about the early 1950s to 1993 and then a decreasing trend through to the present, with an historic high return in 2010 that produced a large return in 2014 (Fig. 8). In 2009, there was an unexpected very poor return after two previous poor returns. The poor returns and the inability to forecast the poor returns, so alarmed all involved that the Prime Minister of Canada commissioned a judicial enquiry to determine why the declines were occurring. The enquiry started its hearings in the summer of 2010, several months before the historic high return of 2010 (Fig. 8). The reasons for the historic high return were not considered. After two years and a cost that probably exceeded 40 million dollars, the judge considered that the reason for the poor return in 2009 was that ocean and climate conditions may have resulted in abnormally low phytoplankton and nitrate concentrations that could have led to poor zooplankton production (Cohen 2012). However, most people remember the judge’s statement “some, I suspect, hoped that our work would find the “smoking gun”—a single cause that explained the two-decade decline in productivity”. The judge could have equally included the previous three-decade increase in productivity. The message from this judicial exercise is that the judge did not identify the reason for the declining trend because he did not hear any scientific explanation of the mechanisms causing the declining trend. Thus, the importance of the inquiry may be not what was found but what was not found.

[Graph showing total return of sockeye salmon to the Fraser River, 1952–2016.]

There is a recent unpublished study by Lyse Godbout at the Pacific Biological Station in Nanaimo that is a clue to what caused the very poor return in 2009 and the exceptionally large return in 2010. She found that the juveniles that produced the very poor return had very poor growth in the early marine period in the Strait of Georgia, while the juveniles that produced the very good return in 2010 had significantly greater growth in the early marine period. This is not an explanation of the trends, but it is evidence that individuals that have very good survival also have very good growth in the first four to six weeks in the ocean.

Summary

Production trends, as shown in the preceding examples, occur for different species of Pacific salmon in different oceans. Obviously the circumstances causing the trends may differ, but I propose that the underlying mechanisms that control the response of the individuals to the changes in their ecosystems may be similar. As mentioned previously, we cooperate internationally to solve important common problems such as complex medical issues. We could use the International Year of the Salmon to create teams that would use the same kind of
international cooperation used for medical problems to identify the mechanisms that cause these trends and regulate Pacific salmon production. The message is that finding a cure for something is much easier when the cause is known.

2—Hatcheries and salmon enhancement

Hatchery reared Pacific salmon are now estimated to represent about 40% of the biomass of all Pacific salmon in the subarctic Pacific (Ruggerone and Irvine 2018). This clearly indicates that hatchery fish are a major contributor to the commercial and recreational economies of Pacific salmon producing countries. Hatchery production generally is considered to be a technology-based effort, inferring that the information needed to produce hatchery fish is mostly known. In contrast, wild salmon are recognized as being challenged by changing freshwater and ocean ecosystems with the understanding that there will be substantial changes to ocean ecosystems. For example, model predictions indicate that by 2050, most of the surface waters of the North Pacific will be 1.2 to 1.8 °C warmer (www.esrl.noaa.gov/psd/ipcc/). Thus, there are proposals to change management strategies for wild salmon to use a resilience-based approach and rely less on achieving target escapement numbers (Holling 1973, considered that resilience is the ability to absorb change; I am using the term resilience for hatchery production as the ability to respond to change). A resilience-based approach is intended to ensure more diversity for wild populations with the expectation that within this diversity, (and without understanding the mechanisms involved), there is an inherent ability to better adapt to whatever ecosystem changes occur. I proposed that a similar approach is needed for hatchery production—that is—hatchery production should rely on fish that are best adapted to the changing coastal ecosystems. Not having the natural resilience of wild populations, hatchery production will need to be adaptive and experimental. This may mean that producing hatchery fish is more difficult and expensive, but the production may be necessary to sustain economies if many wild fish populations are not able to adapt to the modern ocean ecosystems. Changing hatchery production from a technology-based approach to an adaptive-based approach is another example of the importance of working together internationally.

Example of hatchery production in Japan

The decline in production of chum salmon in Japan, discussed previously, (Fig. 2) could be explained as an inability of the chum fry to adapt to recent ecosystem changes in the coastal areas around Japan. There is a possibility that the decline in production is also related to their residency in the Sea of Okhotsk after they leave the coast of Japan. A paper by Shuntov et al. (2018) summarized the biological information collected from numerous scientific surveys starting in the 1980s by the Russian scientists from TINRO in Vladivostok. Using extensive nekton data and over 300,000 stomach analyses, they concluded that competition for food is not the most important factor limiting the abundance of juvenile Pacific salmon in the Sea of Okhotsk because there is no evidence of acute food shortages. For example, a possibility is that the Japanese fish are more susceptible to predation when they enter the Sea of Okhotsk, because they are less able to avoid predation. Identifying the reasons for the declining production of Japanese chum salmon is of international importance as the decline shows that large scale changes in hatchery production are possible throughout the North Pacific. A resilience-based approach would consider experimenting with stocks that are better adapted to growing faster and quicker when they enter the ocean. Understanding the mechanisms involved and using this understanding to release fish that are metabolically better adapted to survive in the changing coastal ecosystems may be the approach needed by all hatchery production in the future.

Example of hatchery production in British Columbia

A second example of the need to be more adaptive when producing hatchery fish is the history of producing hatchery Pacific salmon in British Columbia. In mid-1970s, the Canadian Government was advised that there was unused capacity in the ocean that could produce more Canadian Pacific salmon. The government was advised that the fastest way of producing more fish for the various fisheries was to produce hatchery fish. The Salmon Enhancement Program was officially started in 1977 and was expected to double the current commercial catch by 2005 with increases in abundance of all five species of Pacific salmon. By 2005, the commercial catch was less than ½ of the catches in the 1970s (data from NPAFC Pacific salmonid catch statistics, updated 31 July 2018). There is no explanation of what went wrong. However, the current record high catches of Pacific salmon by all countries, which are about double the catches in the 1970s, are evidence that the carrying capacity of the North Pacific for Pacific salmon in the 1970s was capable of producing more salmon as originally thought. My interpretation of the failure to double production and the actual decline in production is that the capacity to support juveniles in the early marine period in the coastal areas of British Columbia declined in the 1980s resulting in higher marine mortality.
rates and reduced abundances. Similar to the situation in Japan, it may be possible for Canada to improve hatchery production on the Pacific coast if they become more adaptive by looking for ways to improve the growth of juveniles in the early marine period.

Summary

These two examples highlight the difficulties with the production of hatchery fish that have limited resilience to changing ocean ecosystems. With the almost certainty of major changes in ocean ecosystems, it is also almost certain that there will be more difficulties producing hatchery fish. I suggest that as part of an international effort to understand the mechanisms that regulate Pacific salmon production, there could be an increased focus on maintaining hatchery production in changing ocean environments. A new approach would be more adaptive. Key to this approach would be that hatchery production would be continuously experimental. Hatchery production would become a series of experiments making production more difficult, but eventually more predictable. Hatchery production could change from producing fish with homogeneous life histories to populations of fish with diverse life histories. The intent would be to improve the early marine survival. Importantly, adaptive hatchery production becomes more than releasing a suite of fish of populations at different times, as the approach is to ultimately understand the mechanisms that regulate the production and using the understanding identify populations that are best adapted to existing ecosystems. Importantly, there needs to be a greatly increased scientific interest in optimizing hatchery production in the changing ocean ecosystems. This could begin with an international symposium that is privately funded so that all experts can participate.

Richard Feynman was a Nobel Prize winning theoretical physicist. He responded to a question during one of his lectures by saying that, in general, he would look for a new law of physics by guessing the relationship and then computing the consequences. If the computations or experiments did not support the guess or hypothesis, then it was wrong. This is the approach we need to take as an international team of researchers to discover the mechanisms that regulate Pacific salmon abundance.

The critical size-critical period hypothesis originally proposed by Beamish and Mahnken (2001), was revised to emphasize the rate of growth up to a critical threshold which would be the critical period (Beamish and Neville 2016). The principle would be that rapid growth up to the critical period would ensure that the condition of the individual exceeded a metabolic threshold. Individuals with a condition exceeding the threshold would begin to store more lipids than individuals not exceeding the threshold. Fish that stored more lipids would have a better chance of surviving the first ocean winter. Fish not exceeding the condition the threshold would continue to use more lipids for somatic growth and consequently would have lower lipid levels in the winter and be more susceptible to mortality. I sometimes use the expression “dead fish swimming” to categorize the fish that were not programmed to store lipids for the winter. The intent of the revised hypothesis is the same as the original proposal, except that size relates to the amount of growth and condition that would allow an individual to exceed a critical threshold at a critical period. The critical period component of the hypothesis continues to be a genetically programmed threshold that is cued by an environmental stimulus such as day length at a genetically determined threshold in development. An individual that grows faster in the first weeks in the ocean, by maximizing energy used for growth, survives better because it can be larger and reduce predation threats and because metabolism is changed to begin to store more lipids. Critical sizes, metabolic thresholds, decision windows and similar concepts are commonly recognized mechanisms. It was relatively easy to find over 75 papers that addressed the topic of size thresholds and critical periods. For example, a well-known paper by Lorenz (1937), reported that “imprinting of an animal occurs only during a narrow defined period in the individual’s life, the critical period, and the imprinted behaviour cannot be forgotten”. His research showed that there are metabolic pathways that are programmed to be receptive for a very brief period. In another study, Shearer and Swanson (2000) hypothesized “that a metabolic hormone may be a critical signal to the reproductive system that there are sufficient energy reserves or that growth rate is sufficient to initiate maturation for the subsequent years”. These authors and others have reported that decisions to mature can be many months before the fish begin to show signs of maturing. In the third example, Silverstein et al. (1998) hypothesized that sexual development of Chinook salmon occurs in two critical periods leading to gonadal development and sexual maturity. These critical periods would be set by environmental cues and at the critical period, individuals evaluate their development potential in terms of growth rate, size or stored energy or some combination of factors.

The critical size-critical period hypothesis could be a major mechanism regulating all salmon production. It would mean that fish that grow faster, quicker when they first enter the ocean, survive better. As Richard Feynman,
advised, hypotheses need to be tested. According to the hypothesis, Japanese chum salmon production gradually declined because the growth rate of the fry when they entered the ocean gradually declined, probably because of reductions in preferred prey. Consequently, more energy was used in finding food and less energy was available for growth resulting in an increasing number of juvenile chum salmon not exceeding a condition threshold at a critical period. A test of the hypothesis would be to compare energy densities of Japanese and Russian chum salmon in the Sea of Okhotsk in the fall. The hypothesis could be supported if the energy densities of the Japanese chum salmon are lower and with a larger variance than the chum salmon from Russia.

4—International cooperation and the International Year of the Salmon

The International Year of the Salmon is intended to draw attention to the commercial and cultural importance of Pacific and Atlantic salmon. Part of this attention will identify the complexities of stewardship in a future of changing ocean and freshwater ecosystems. My original idea in suggesting that there be an International Year of the Salmon was to create opportunities for researchers to work together to understand the mechanisms that regulate the production of wild and hatchery Pacific salmon. Along with some colleagues, I am trying to organize a privately funded expedition to study the ecology of Pacific salmon in the Gulf of Alaska in the winter of 2019. Our main hypothesis is that brood year strength is mostly determined by the end of the first ocean winter. If I can obtain the funds, this will be the first comprehensive study of Pacific salmon in the Gulf of Alaska in the winter, a time when about 1/3 of all Pacific salmon are in the area. There needs to be more of these international expeditions as they will unite the scientific effort to discovering how best to manage wild and hatchery Pacific salmon production as ocean ecosystems change. We also need more international symposia that focus on major issues in the production of wild and hatchery salmon. The symposia need to be privately organized and funded so that all experts and young researchers, soon to be experts, can participate. My suggestion, especially to the younger researchers around the rim of the subarctic Pacific, is that you team up and work out the mechanisms that regulate the production of wild and hatchery Pacific salmon which I think will turn out to be quite simple. If individual researchers show that major advances can be made by teaming up internationally, it may provide the incentive for private funding and future government support.

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The Use of Marine Ecosystem Metrics for Preseason Forecasts of Salmon Harvest

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Annual forecasts of pink salmon (*Oncorhynchus gorbuscha*) harvest in Southeast Alaska (SEAK) and Chinook salmon (*Oncorhynchus tshawytscha*) returns to the Yukon River were developed to advise fishery managers, members of fishing industries, and the public. Although the forecasts were developed independently for different species and widely separated geographic localities (Fig. 1), the projects illustrate the utility of using marine ecosystem metrics for forecasting future harvests of salmon and how to effectively communicate results and uncertainty to stakeholders.

Fig. 1. Two regions in Alaska where salmon forecast models were performed: pink salmon harvest in Southeast Alaska and upper Yukon Chinook salmon return strength in the Yukon River in Western Alaska.

Fig. 2. Variability of commercial pink salmon harvest in Southeast Alaska since 1960. Over this period harvests have ranged from 2-95 M fish, with the overall production composition of 97% wild stock based.

The presentation explores the specifics of each example by following a “road map” of steps to connect ecosystem metrics to response variables in order to develop products useful to salmon managers and stakeholders. The roadmap steps are: 1) Identify a problem in need of a solution with climate-driven ecosystem services; 2) Understand and define processes and relationships between climate, fish production and behavior, and fishery performance; 3) Develop research products based on the relationships; and 4) Operationalize research products through timely, dependable delivery to managers and stakeholders.

For the pink salmon fisheries in SEAK, the problem (Step 1) was identified as the high degree of uncertainty introduced into planning for harvesting, processing, and marketing by the high level of variability in annual pink salmon abundances (Fig 2). Motivation to find a solution was added by the large economic value of the fishery with an annual ex-vessel value 10 year average of ~$44 million, and the importance of pink salmon to the ecosystem. The mechanism by which climate drives fish behavior (e.g., ocean distribution of juvenile abundance) and subsequently, fishery performance, has historically been poorly understood. We hypothesized (Step 2) however, that mortality of pink salmon during their early marine phase is high, variable, and a primary driver of year class strength. Thus, after this critical early period, surveys that assess juveniles during their seaward migration were expected to be more effective predictors of adult returns (i.e., year class strength). However, ocean conditions during the subsequent (first) winter of ocean residence could still demonstrate impacts. Through research (Step 3) the result was readily identified as an accurate and reasonably precise forecast of annual harvest (Fig. 3). The pink salmon harvest forecast model is based on a juvenile abundance index (from surface trawl surveys) adjusted for...
temperature (Fig 4). Information on juvenile growth condition, diet, prey availability, and climate indices are included as ecosystem considerations of the forecast (Orsi et al. 2017). The research was operationalized (Step 4) through timely communication with the Alaska Department of Fish & Game (ADFG) so the survey information could be incorporated into their forecasts (10 months prior to the fishery). As a final step in operationalizing the forecast, the pre-season pink salmon forecast was presented to resource stakeholders at the SEAK Purse Seine Task Force Meeting (seven months prior to fishery) and simultaneously communicated via a forecast webpage.

Fig. 3. Pre-season harvest forecast of pink salmon to Southeast Alaska (circles) with 80% confidence intervals and the actual harvests seven months later (bars). 2014-2016 had anomalous warm water summer and winter temperatures.

Fig. 4. Southeast Alaska Pink Salmon Harvest Forecast Model (CPUE +Temperature).

Fig. 5. Yukon River Chinook salmon harvest.

Fig. 6. Canadian-origin juvenile index in the northern Bering Sea (average cv of 23%).

For Yukon River Chinook salmon, the problem (Step 1) was identified as large inter-annual fluctuations in run strength and subsequently, harvest (Fig 5). A sense of urgency in finding a solution has been fueled by a decline in abundance to levels low enough to precipitate a Federal disaster declaration for the fisheries. Further urgency is added by the presence of an international treaty with Canada that requires U.S. fisheries to pass a minimum number of adult Upper Yukon (Canadian-origin) Chinook across the Canadian border each year which has become difficult with abundance declines. As with southeast Alaska pink salmon, a lack of mechanistic understanding (Step 2) of relationships between climate, fish behavior (juvenile abundance and ocean distribution) and fishery performance (adult production) for Yukon Chinook was addressed by using the hypothesis that mortality during Chinook salmon’s early marine life history is
high, variable, and affects year class strength. After this critical early period, surveys of juvenile abundance in the northern Bering Sea can inform predictions of year class strength. However, ocean conditions can also impact fish during the first winter of ocean residence and drive variability in forecasts. Using research (Step 3), a time series of juvenile Chinook salmon abundance was constructed for the Canadian-origin (Upper Yukon) stock group for late-summer (typically during the month of September) pelagic rope trawl surveys in the northern Bering Sea, (BASIS) from 2003–2017. Abundance is estimated from trawl catch-per-unit-effort data, genetic stock composition, and mixed layer depth. Juvenile Chinook salmon abundance estimates for the Canadian-origin stock group have ranged from 0.6 million to 2.6 million juveniles with an overall average of 1.5 million juvenile Chinook salmon from 2003 to 2017 (Fig. 6). The Canadian-origin juvenile abundance index is significantly correlated with adult Canadian-origin returns (Fig. 7) which facilitates a forecast of future returns of the Canadian-origin stock group to the Yukon River (Fig 8). To operationalize the research (Step 4) this forecast was presented to the Yukon River stakeholders through the Yukon River Joint Technical Committee.

![Graph showing relationship between juvenile abundance and adult returns.](image1)

**Fig. 7.** Relationship of Canadian-origin juvenile index and adult returns.

![Graph showing accuracy of juvenile index forecast to adult returns.](image2)

**Fig. 8.** Accuracy of Canadian-origin juvenile index forecast to adult returns of the last three years and future predictions.

*Note: The views expressed in this abstract are those of the author and do not necessarily represent those of National Oceanic and Atmospheric Administration (NOAA).*

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Estimating Exposure of Interior Fraser River Steelhead to Strait of Georgia and Fraser River Commercial Fisheries from 2004–2016

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Keywords: steelhead, exposure model, Fraser River, Bayesian hierarchical model, fisheries management

An objective of the Southern British Columbia Salmon Integrated Fisheries Management Plan (IFMP) is to minimize the impact of Canadian fisheries on Interior Fraser River (IFR) Steelhead to increase their spawner abundance. For Fraser river commercial gillnet fisheries, the current strategy is to protect 80% of the IFR Steelhead run with a high degree of certainty (DFO 2017a). The IFR Steelhead run is composed of three populations: Thompson, Chilcotin, and West Fraser.

Steelhead are not targeted by Canadian commercial fisheries (CCFs) but occur as bycatch in various salmon-targeted fisheries including First Nations Economic Opportunity (EO) fisheries targeting late-run Fraser River Sockeye, Fraser River Pink, and southern B.C./Washington Chum salmon. The main management tool used to protect IFR Steelhead from Fraser River CCFs is to allow only a small window for Chum fisheries, such that 80% of the steelhead run can migrate from the mouth to the spawning grounds without being intercepted. Management actions currently only affect Chum-directed fisheries because they occur at the same time IFR Steelhead are migrating through the Fraser River. DFO is reviewing this strategy for 2018 and considering management actions in marine fisheries and Fraser River fisheries targeting Pink and Sockeye salmon to further protect IFR Steelhead. The purpose of this work was to explore the likelihood of IFR Steelhead exposure to other commercial/EO fisheries that occur along their migration route, in addition to the Fraser River Chum-directed fisheries.

Fig. 1a. Map of Fisheries and Oceans Canada South Coast fishery management areas (British Columbia, Canada). Waters shaded in blue were included in the IFR Steelhead exposure model. Management Area map adapted from maps by Fisheries and Oceans Canada (2017b). Inset from Rhemtulla et al. (2001).

Fig. 1b. Map of lower Fraser River (British Columbia, Canada). Waters shaded in blue were included in the IFR Steelhead exposure model. Adapted from Barker (2012). Inset from Rhemtulla et al. (2001).

The current iteration of this model examines fisheries within the Strait of Georgia ("northern route") and Fraser River in British Columbia, Canada (Fig. 1). This includes five commercial fishery management areas (Areas B, D, E, G, H), and three First Nation EO fisheries from the mouth of the Fraser River to Sawmill Creek (Below Port Mann gill net (BPM GN), Above Port Mann gill net (APM GN), and Above Port Mann beach seine (APM BSn)). Each fishery was further sub-divided by target species (Sockeye, Pink, and Chum salmon), for a total of 24 fisheries. An approximate migration path through the fishing areas was measured and binned into 1 km increments using the measuring tool in Google Earth Pro (Google Inc. 2017). For example, management Area 12-12 (Bate Passage) begins at km 33 and ends at km 38. Fisheries occurring on the West and South coast of Vancouver Island ("southern route") were excluded from this first iteration of the model due to a lack of information about the
proportion of IFR Steelhead migrating along each route (i.e., diversion rate). The starting point of migration through the CCFs (km = 0) is the Northwest corner of Area 11-1 (51°09'48.90" N, 128°04'8.10" W); the migration route examined extends approximately 625 km, ending at Sawmill Creek (49°36'42.87" N, 121°24'35.86" W).

Published estimates of upstream Steelhead migration speed are highly variable, depending for example on the river system, freshwater or marine environment, population, and water temperature. Median and mean estimates range from 6.2 km/d to 36.6 km/d (e.g., Spence 1989, Burgner et al. 1992, Walker et al. 2000, Renn et al. 2001, English et al. 2006). Limited data is available on Steelhead migrating in the area examined in this analysis (Fraser River above Harrison confluence, Renn et al. 2001); therefore, for this model we employed a hypothesis about migration speed based on a similar co-migrating species for which there is tagging data, the Chum salmon. In the freshwater environment (currently approximated as the Fraser River upstream of Albion), variable migration speed was assumed to follow a normal distribution with mean 20 km·d⁻¹ and SD 3 km·d⁻¹ (Rosberg and Greer 1985). In the marine environment, variable migration speed is assumed to follow a normal distribution with mean 34.8 km/d and SD 4.1 km/d (Van Will unpublished data).

A common approach to estimating the annual 50% date (date when half of the return is expected to have passed the reference point) and spread (or duration) of fish migration is to fit a normal distribution to catch data (Mundy 1979, Cave and Gazey 1994, Hilborn et al. 1999, Gazey and Palermo 2000). The reference point for IFR Steelhead migration is the Albion test fishery, 60.4 km upstream from the mouth of the Fraser River. To characterize IFR Steelhead migration, a normal distribution was fit using a Bayesian hierarchical approach to 22 years (1995–2016) of Steelhead catch data at the Albion test fishery. Gazey and Palermo (2000) details the fishery operation. The historic information from the Albion test fishery characterizes the variability of the run timing of steelhead from year to year, and the Bayesian approach reduces uncertainty in the timing estimates when annual encounters are low.

Fishery opening information for 2004 to 2016 was obtained from Fisheries and Oceans Canada's Fishery Operating System. Visual Basic for Applications (VBA) was used in Microsoft Excel to convert opening information from date and time into a cumulative hour, starting from 15 July 00:00 as hr = 0, 15 July 01:00 as hr = 1, etc. The ending hour, hr = 3335, is equivalent to 30 November at 23:00. Opening data were transformed using VBA into a matrix of 0’s and 1’s where 0 = closed and 1 = open. One matrix was created for each of the 24 fisheries for each year.

The movement speed and migration hour past Albion for a simulated run of 1000 Steelhead was estimated by drawing from the normal distributions outlined above. The time when each fish would have likely been located at each km increment (T₂) was then calculated based on the estimated time the fish passed Albion (T_{Albion}) and migration speed:

Migration downstream of Albion: \[ T_2 = T_{Albion} - \frac{\text{speed}}{\text{km}_2 - \text{km}_{Albion}} \]

Migration upstream of Albion: \[ T_2 = T_{Albion} + \frac{\text{speed}}{\text{km}_{Albion} - \text{km}_2} \]

This information was cross-referenced with the opening matrices to determine if there was also a fishery open in the same location at the same time, which would indicate the fish was exposed to an open fishery.

**Fig. 2.** Preliminary estimates of the mean (+/- 1 SD) of estimated 50% dates of the IFR Steelhead return to the Albion test fishery, 1995–2016.

**Fig. 3.** The mean (+/- 1 SD) of estimated variability of the IFR Steelhead return to the Albion test fishery, 1995–2016.
The proportion of the run exposed to each fishery was estimated annually. A migration pattern for the run was drawn from the historical distribution of run spread and 50% date estimated for each year to generate 3000 simulated patterns of IFR Steelhead migration. Each hypothesis about residence time was evaluated in terms of these 3000 simulated returns and the proportion of the run exposed to each fishery was recorded. Using these results, the cumulative exposure of each fish to fisheries each year was also estimated by counting whether each fish would have been susceptible to capture in a particular fishery (i.e., Area D Chum, Area B Sockeye, etc.) and determining the proportion of the run that may have been exposed to no fisheries, 1 fishery, 2 fisheries, etc.

Estimates of 50% dates of return to Albion ranged from day 266 (23 September; 22 September in leap years) to day 299 (26 October; 25 October in leap years). Several years had high variability in this estimate owing to a lack of encounters in the Albion test fishery (Fig. 2). Variability around return dates did not vary much among years, ranging from 7.9 days to 10.6 days (Fig. 3), but uncertainty was high for all years.

Table 1. Preliminary estimates of mean % exposure of Steelhead to commercial Chum-directed, Sockeye-directed, and Pink-directed fisheries, from 2004–2016.

<table>
<thead>
<tr>
<th>Fleet</th>
<th>Chum-directed</th>
<th>Pink-directed</th>
<th>Sockeye-directed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean % exposure</td>
<td>SD</td>
<td>mean % exposure</td>
</tr>
<tr>
<td>Area H</td>
<td>52.2</td>
<td>20.8</td>
<td>11.5</td>
</tr>
<tr>
<td>Area D</td>
<td>35.5</td>
<td>22.3</td>
<td>6.7</td>
</tr>
<tr>
<td>BPM GN</td>
<td>25.2</td>
<td>16.8</td>
<td>23.9</td>
</tr>
<tr>
<td>Area B</td>
<td>24.6</td>
<td>12.2</td>
<td>12.1</td>
</tr>
<tr>
<td>APM GN</td>
<td>10.2</td>
<td>5.7</td>
<td>-</td>
</tr>
<tr>
<td>Area E</td>
<td>7.1</td>
<td>5.1</td>
<td>6.9</td>
</tr>
<tr>
<td>APM BSn</td>
<td>5.3</td>
<td>3.4</td>
<td>-</td>
</tr>
<tr>
<td>Area G</td>
<td>-</td>
<td>-</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Fig. 4. Cumulative exposure of IFR Steelhead to marine and in-river commercial fisheries from 2004–2016. Legend indicates the number of fisheries.
Preliminary reconstructions of simulated IFR Steelhead exposure to actual fisheries each year suggested that on average, some fishing fleets (e.g., Area H, Area D, BPM GN) and Chum-targeted fisheries were much more likely to expose a large proportion of the run to fishing activity than other fleets (Area G, Area E) and Sockeye- and Pink-targeted fisheries (Table 1). IFR Steelhead were not likely exposed to more than seven fisheries within a year (Fig. 4). Further, at least 60% of the run was likely exposed to three or fewer fisheries every year. This did not change much with run timing variability. This model could be adapted to forecast potential relative impacts of fishing plans using the average run timing distribution based on 22 years of historical data. It could examine exposure in both a suite of fisheries (e.g., Area B Chum, Area D Sockeye, BPM GN Chum, etc.) and within a specific fishery (e.g., alternative plans for Area B Chum). The model could also be adapted to monitor patterns of exposure over time.

This approach is not without limitations; some of the concerns with using an exposure model include: (1) annual run sizes are unknown; and (2) this model does not estimate the harvest rate for IFR Steelhead. Reliable estimates of fishery-induced mortality to estimate catchability by gear type would be needed to estimate the actual impacts. Both of the above point strongly to the need for fisher-independent information about steelhead encounters.

In summary, a preliminary analysis of historic return patterns and fishery plans suggests that some fisheries are much more likely to expose a large proportion of the IFR Steelhead run to fishing activity than others, and that extending the current in-river management objective to other commercial fishing areas will require careful consideration of other factors along with exposure (e.g., gear type, fishing effort). Additionally, migration speed assumptions may strongly influence exposure estimates, warranting further exploration with a sensitivity analysis.

REFERENCES


Effects of Duration of Net-pen Acclimation and Timing of River Stocking on Early Growth and Adult Return of Chum Salmon along the Pacific Coast of Honshu, Japan

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Keywords: chum salmon, juvenile abundance, early growth, return rate, stocking strategy

The number of chum salmon (Oncorhynchus keta) returning to the Pacific coast of Honshu, Japan, in the southernmost part of this species’ distribution, has decreased notably in recent years. One reason is the decline in stocked fry following the tsunami disaster of March 2011; another possible reason is the changing coastal environment. A recent study pointed out that warm water during the coastal residence period of juvenile chum salmon could be negatively affecting their early survival off Iwate Prefecture, northeast Honshu, Japan (Wagawa et al. 2016). To adapt to the changing coastal climate, we should reconsider the release timing of stocked salmon fry from rivers. Along the Pacific coast of Honshu, however, salmon fry are also stocked from net pens in near-shore areas, as well as from the rivers, because of local geographic conditions: a deeply indented rias coastline has developed in this area, and many of the small inlets and bays are suitable for net-pen acclimation. Net pens can supply the fry capacity of hatchery ponds and maintain hatchery fry densities at the appropriate level, but there are costs for feeding fry and maintaining the pen nets. To facilitate cost-effective fry production and improve adult return of chum salmon, we modified the present stocking program and developed new strategies, especially focusing on the duration of net-pen acclimation and the timing of river stocking.

For the 2012–2016 year classes, we tested two stocking programs in Iwate Prefecture, one in Yamada Bay and the other in the Orikasa River: 1) short-term net-pen acclimation, where fry were acclimated to seawater in a net pen for one week before release in the bay (shorter than the usual four weeks), and 2) early release, where fry were released into the river in February (earlier than the usual middle March–early May). We collected juveniles in the bay for about 40 days after release and measured growth rates by otolith daily-ring analysis. Fry capture and growth rates, and adult return rates of the test groups were compared to those of control groups (the usual river release, and four-week net-pen acclimation, released in April or May). Capture rates of both short-term and four-week acclimation were slightly higher than those of usual river release, suggesting that net-pen acclimation decreases early mortality. On the other hand, growth rates of fry of four-week net-pen acclimation in 2012 and 2013 year classes were substantially lower than those of one-week net-pen acclimation and usual river release. In age-4 adults of both 2012 and 2013 year classes, river return rates from one-week net-pen acclimation were 1.9 times that from the usual four-week acclimation. The return rate from usual river release was at a level similar to that of one-week net-pen acclimation in the 2012 year-class, but double in the 2013 year-class. One possible reason for lower growth and return rates in the four-week net-pen group compared to the one-week group is deterioration of habitat inside the net pen during the four-week acclimation, caused by bio-fouling of the net, and/or an excess of fry biomass after four weeks of growth. Growth rates of the early release group were generally lower than those of the April–May release groups. The low growth rate of fry released in 2014 was probably because of low temperature, but those in 2015 and 2016 may have been caused by low food availability. The return of adults of the early release group will be monitored. These results indicate that the duration of net-pen acclimation and the timing of stocking are important in determining early growth and survival of chum salmon. This study was supported by the Great East Japan Earthquake Reconstruction Project sponsored by the Agriculture, Forestry, and Fisheries Research Council, Japan.

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REFERENCES

International Year of the Salmon Survey of Fisheries and Oceans Canada Salmon Staff Identifies Collaborative Opportunities and Possible Next Steps

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Keywords: International Year of Salmon, Survey, Collaboration, Knowledge Sharing, Knowledge Discovery, IYS

Preliminary analysis of results from a 2017 International Year of the Salmon (IYS) survey confirmed collaborative opportunities exist that should allow Fisheries and Oceans Canada (DFO) to better understand and manage salmon populations.

Using Survey Monkey, we asked 351 staff from across the country who work on Pacific or Atlantic salmon if they saw potential for collaboration on 37 topics within six IYS themes (i.e., Status of Salmon, Salmon in a Changing Salmosphere, New Frontiers, Human Dimensions (connecting salmon with people), Information Systems, and Salmon Outreach and Communication). Response rates among six job types (resource managers, line managers, scientists, science biologists, technical staff, hatchery staff) and seven regions (Pacific (British Columbia/Yukon), Central and Arctic, Ottawa, Gulf, Maritimes, Quebec, Newfoundland and Labrador) were similar (~40%); 124 surveys nationally were usable for analyses including 90 from the Pacific Region.

Responses to the query of potential enhanced collaboration were scored as (score; figure label in brackets): no or not applicable (0; NA); yes but unlikely at present (1; pending); yes and I have activity that would benefit (2; need); yes and I can help others (3; offer); and yes collaboration is vital to my work and should be high priority to DFO (4; critical). Various analyses were applied to the 124 by 37 matrix of answers, including heat maps factored by job types within regions (see the example, Fig. 1) and scoring the topics as weighted means for the answers (weights 0 to 4). Here we present preliminary findings from the analysis of results from the Pacific Region, which had by far the largest sample size (n = 90).

Fig. 1. Cluster analysis of responses to opportunities for collaboration for 37 topics related to salmon. The “no” answers were deleted in this example to emphasize clusters where collaboration was favored. Clustering is by the order of topics, the columns correspond to the available answers (pending, need, offer, and critical). Highest scored topics indicated by dark red purple.
Table 1. The most important IYS themes and topics from a collaborative perspective identified in a survey of DFO staff from the Pacific Region and corresponding job types for whom these themes and topics were most important.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Job Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Salmon Status</td>
<td>Hatchery Staff, Scientists</td>
</tr>
<tr>
<td>2. Information Systems</td>
<td>Technical Staff, Biologists</td>
</tr>
<tr>
<td>3. Outreach and Communications</td>
<td>Scientists, Hatchery Staff, Managers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topics</th>
<th>Job Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Field Data</td>
<td>Hatchery Staff, Resource Managers</td>
</tr>
<tr>
<td>2. Data Analysis</td>
<td>Biologists, Technical Staff</td>
</tr>
<tr>
<td>3. Science Communication</td>
<td>Managers, Biologists, Scientists, Hatchery Staff</td>
</tr>
</tbody>
</table>

Salmon Status, Information Systems, and Outreach and Communication were the three most important IYS themes identified from a collaborative perspective while Field Data Collection, Data Analysis, and Science Communication were the three highest ranked topics (Table 1). These results suggest a need for improved collaboration in the flow of information at multiple stages with respect to salmon assessment, management and research (Fig. 2). For instance:

- Various types of Field Data and other information are collected—technicians, biologists, and resource managers identified this as the most important topic for collaboration.
- The information collected needs to be stored in Information Systems and analysed. In highlighting the potential benefits of collaborating on Data Analysis and the Information Systems theme, technical staff and biologists appear to be asking for collaboration support.
- These data are important in determining stock status, and this information needs to be communicated outwards, as identified by managers, biologists and scientists, and hatchery staff.

Fig. 2. Information flow for salmon management, from gathering information to making decisions. Our analysis of the survey data indicated a need for improved collaboration at multiple stages in this flow of information.

How then to improve the flow of information?

A working prototype of new web-based technology for knowledge sharing (Fig. 3) was applied to a subset of data gathered during our surveys. RoundTable™ can deal with diverse kinds of data as a network where there are many nodes of many different types (with extensive properties), which are richly linked together, and then cross-linked to ideas (Fig. 4). Further, the nodes representing ideas are linked into a semantic web. The technology has an appropriate tagline: Connect the dots. All the dots (https://www.roundtable.eco/). Users can view this diversity and complexity (and realism) as tables, graphs or potentially many other interactive data visualizations to support their discovery and sharing of knowledge.
Fig. 3. Example of how information can flow from who (i.e., named individuals, groups, and organizations) to what (i.e., activities (projects), events, products) to where (locations or sites). These links can be customized for each analysis.

Fig. 4. Results from preliminary analysis of survey data displayed as a Knowledge Graph in bottom left hand corner and a blown-up fragment of it (main figure) showing Persons linked to Specific Ideas they proffered, with those Ideas further linked by more General Ideas. Thus people (activities etc.) can be linked by chains of ideas.

Next steps will hopefully include using RoundTable™ or similar software to manage a more complete listing of salmon activities (projects). The approach could be extended to others outside DFO who work on salmon, potentially expanding the emerging “DFO Salmon Network” to one with national or international membership. It is our contention that identifying connections among activities and people should result in new and improved partnerships that will improve our ability to manage salmon in an uncertain future.
Increasing Outreach: Non-Salmon Species in the Subarctic North Pacific

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Keywords: North Pacific Fisheries Commission, Pacific saury, chub and spotted mackerels, Japanese sardine, neon and Japanese flying squids, North Pacific armorhead and splendid alfonsino

A multinational salmon survey in the North Pacific planned as a part of the International Year of the Salmon (2014 and 2015) initiative provides an opportunity to collect valuable data on non-salmon species in the Subarctic North Pacific. The North Pacific Fisheries Commission (NPFC) is considering taking part in the survey to obtain new data and improve knowledge on NPFC’s species of interest. The goal of this study is to review the past pelagic surveys conducted in the North Pacific with the emphasis on the period from January to March and find out what can be expected from the participation of NPFC in the NPAFC IYS survey.

The study was mostly based on data from the Russian pelagic expeditions in the high seas of the western and central Pacific Ocean from 1969 to 2017. There were 150 pelagic surveys conducted entirely or partly in the high seas, beyond exclusive economic zones, in those years. For more details on materials and methods, you can refer to Shuntov and Bocharov (2005). In addition to the Russian surveys, available published information on non-salmon species caught in the Japanese trawl and gillnet surveys has been reviewed (Ueno et al. 1996; Ishida et al. 1998; Fukuwaka et al. 2006; Murakami et al. 2016).

During the Russian surveys, a total of 947 species of fish, squids, crustaceans and other marine species, which are formally under the NPFC mandate, were caught in the high seas from 1969 to 2017. These include eight priority species for the NPFC Scientific Committee: Pacific saury, chub and spotted mackerels, Japanese sardine, neon and Japanese flying squids, North Pacific armorhead and splendid alfonsino. The mackerels, Japanese sardine, and splendid alfonsino had the highest occurrence and were registered about 2500, 1700, and 1600 times, respectively.

From January to March, chub and spotted mackerel, Japanese sardine, and Japanese flying squids were the most abundant in the western North Pacific (Fig. 1). They all are straddling stocks, and their abundance in the EEZs is also high, although it is not shown as the study was focused on the NPFC Convention Area. Pacific saury and neon flying squids had wider distribution. They were abundant in both western and central parts of the North Pacific. Most catches of splendid alfonsino occurred in the Emperor Seamounts area, but some fish were registered in the western North Pacific. Armorhead were caught only once in the period from January to March.

Published information about non-salmon species from the past winter salmon surveys conducted by Japan is limited. According to the results from three Japanese surveys conducted in 1996, 1998, and 2006 (Ueno et al. 1996; Ishida et al. 1998; Fukuwaka et al. 2006), 17 fish species were found in these surveys in the North Pacific. The number of squid species caught was seven. There also were different species of Coelenterata and Appendicularia. In total, at least 26 species were caught during these surveys. However, apparently, the number of species is actually larger as not all of individuals caught were identified and consequently were recorded as one group. All these species are under the NPFC mandate and therefore this data is of potential value for the NPFC. In addition, Murakami et al (2016) reviewed Japanese trawl and gillnet surveys conducted in 1980–2014 and found out that North Pacific armorhead regularly occurred as bycatch.

Therefore, from the data collected during the Russian and Japanese winter salmon surveys, all priority species of NPFC were caught in the NPFC Convention Area in the past. List of species caught also includes a lot of other species of NPFC mandate which potentially can be used by NPFC in the future.

Potential outputs for NPFC from joining the project could include improved knowledge about distribution and migration of priority species, validation and adjustment of models (ecosystem, suitable habitats etc), new biological

1Fisheries resources covered by the NPFC are all fish, mollusks, crustaceans and other marine species caught by fishing vessels within the Convention Area, excluding: (i) sedentary species insofar as they are subject to the sovereign rights of coastal States; and indicator species of vulnerable marine ecosystems as listed in, or adopted pursuant to the NPFC Convention; (ii) catadromous species; (iii) marine mammals, marine reptiles and seabirds; and (iv) other marine species already covered by pre-existing international fisheries management instruments within the area of competence of such instruments.
information for priority and other species of fish and squids, and other data related to oceanography, fish diets, and zooplankton.

The IYS could benefit from cooperation with the NPFC through increased outreach and higher involvement of regional stakeholders, collaborative studies on marine ecosystems and modeling, development of integrated information systems and strengthened ties between NPAFC and NPFC. It could be of direct benefit to Canada, Korea, Japan, Russia, and the USA as they are members of both NPAFC and NPFC.

Fig. 1. Catch distribution of some NPFC priority species in the high seas of the North Pacific from January to March in 1969–2017, ind./hour of trawling
REFERENCES


Homing Ability of Japanese Chum Salmon and Differences in their Return Timing by Reproductive Season

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Keywords: chum salmon, homing, natal tributary, otolith thermal marking, straying

To increase their harvest, the juveniles of chum salmon are stocked in several tributaries of river systems, and homing adults are captured from each tributary for hatchery broodstock. Therefore, it is important to understand the homing behavior of chum salmon for a successful management of their resources. In this study, I surveyed the homing ability of chum salmon and differences in their return timing by reproductive season.

Fig. 1. Map of the Gakko River system, Yamagata Prefecture, Japan. Yellow stars and black rectangles indicate the hatcheries and weirs from where chum salmon adults were collected for hatchery brood stocks. Note that the confluence of the Araisawa River with the Gakko River is only 2.3 km from that of the Takase River.

The study was conducted in the Gakko River system, Yamagata Prefecture, Japan. There are three hatcheries in the Gakko River system, the Minowa hatchery on the Ushiwatari River, Masukawa hatchery on the Takibuchi River, and Takase hatchery on the Takase River (Fig. 1). Seven groups of chum salmon juveniles with unique otolith-thermal-marking depending on their natal tributary (hatchery) and date of reproduction were released through each hatchery discharge channel in 2009–2011 (Iida et al. in press). The number and mean body weight of chum salmon of the seven groups ranged from 82 thousand to 1.8 million and 1.0 to 1.7 g, respectively. The returning adults were captured each year between October and January at weirs of each of the three tributaries (Fig. 1). One hundred adults (50 males and 50 females) were sampled every ten days; their age was determined by analyzing their scales, and the otoliths were checked to identify the origin of the specimens in 2011–2015. Referring to Morita et al. (2015), the number of escapements of the groups in each tributary ($E_{g,r}$) was estimated as:

$$E_{g,r} = \sum_{i} \sum_{j} p_{M,g,r,i,j} \cdot y_{M,g,r,i,j} + \sum_{i} \sum_{j} p_{F,g,r,i,j} \cdot y_{F,g,r,i,j}$$

where, $p_{M,g,r,i,j}$ and $p_{F,g,r,i,j}$ are the proportion of the otolith-marked male and female fish (g) at age $i$ and season $j$ in a tributary ($r$), respectively; and $y_{M,g,r,i,j}$ and $y_{F,g,r,i,j}$ are the number of male and female fish caught in the tributary ($r$) at season $j$ when the marked fish returned at age $i$.
The median (range) proportion of the group that returned to their natal tributary (i.e., number of escapement to the natal tributary/total number of escapement to the three tributaries) was 86.3% (49.2%–100%, \( n = 7 \)). The results suggest that chum salmon can detect their natal tributary from adjacent non-natal first-order tributaries, and they often stray into second-order tributaries. The peak escapement of the groups was observed during their reproductive season, or just before and after the season of their reproduction. The median (range) proportion of the number of escapements of the groups returning during reproductive season and ten days before and after the reproductive season to the total number of escapements of the group was 84.1% (79.1%–88.9%, \( n = 7 \)). These results suggest that chum salmon can detect their natal tributary, and they return to their natal river during every reproductive event.

REFERENCES


Wrap-up Summary and Research Priorities Identified at the Workshop

Mark Saunders

IYS Director for the North Pacific

The NPAFC-IYS workshop in Khabarovsk was the first of a series of four IYS workshops that will be held in conjunction with NPAFC annual meetings through 2021. One of the reasons for hosting IYS workshops at successive annual meetings is to provide an opportunity to build awareness of the IYS in each NPAFC country and to encourage greater participation by researchers from host countries. This was certainly the case as we had a strong contingent of Russian scientists.

I was both excited and nervous as this workshop represented the beginning of a new process that we expect to be transformative for our approach to research. NPAFC research is guided by a five-year Science Plan that includes goals and research themes. In the past, each country reported annually on activities related to each theme and in the final year of the plan the Science Sub-Committee summarized progress. This retrospective approach was quite challenging. The current plan runs from 2016–2020 and was designed to complement the International Year of the Salmon (IYS) and its five research themes/outcomes. It was decided that annual IYS workshops would provide a good opportunity to document progress on each of the themes and facilitate continuous learning over the four years of the initiative.

Continuous learning is an important element of the IYS, where over its lifetime we want to use a combination of research projects and Workshops/Symposia to achieve IYS outcomes that will collectively establish the conditions for the resilience of salmon and people. This first workshop focussed on the outcome “Status of Salmon”, framed for the North Pacific as “Status of Pacific Salmon and Steelhead Trout”. It will inform subsequent work over the next year to plan and seek funding for projects.

IYS OUTCOMES

<table>
<thead>
<tr>
<th>Status of salmon</th>
<th>The present status of salmon and their environments is understood.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salmon in a changing salmosphere</td>
<td>The effects of natural environmental variability and human factors affecting salmon distribution and abundance are understood and quantified.</td>
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<tr>
<td>New frontiers</td>
<td>New technologies and analytical methods are advanced and applied to salmon research. Research is carried out to fill gaps in poorly studied regions of the salmosphere.</td>
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<td>Human dimensions</td>
<td>Communities, Indigenous Peoples, youth, harvesters, scientists and resource managers across the Northern Hemisphere share knowledge and collaborate in the development of new tools and approaches to restoring, managing and sustaining salmon.</td>
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<td>Information systems</td>
<td>Freely available information systems contain historic and current data about salmon and their environment.</td>
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<tr>
<td>Salmon outreach and communication</td>
<td>People understand the value of healthy salmon populations and engage to ensure salmon and their varied habitats are conserved and restored against the backdrop of increasing environmental change.</td>
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I had the pleasure of chairing a panel discussion at the end of the two days where I asked: What did we learn with respect to our research outcomes? What gaps and resulting priorities did we identify? Often when we attempt to hold plenary sessions of this type, those most fluent in English often dominate. I was very pleased with the lively discussion and scientific debate that engaged people from every country, despite the fact that it was at the end of a very long week for all of us.

Below I provide brief summary statements of what we learned and gaps identified. In October 2018 Theme Counsel Groups will be formed to engage experts from each country in planning for the IYS research themes. I provide some recommended priorities for the Theme Counsel Groups to consider and potentially address through further workshops/symposia or research projects.

As mentioned earlier, the “Status of Salmon” topic was a focus for the workshop. We learned that:
Status appears to be documented to a degree in all regions, with at least catch statistics available to infer status;
Stocks are generally doing better in the north;
Some common trends in many stocks include declining size at age, and shifts to younger age classes;
Chinook exhibit a general trend of poor status;
North American and Russian chum and pink stocks are generally doing well or very well;
Japanese and Korean chum have exhibited declines in recent years; and
There is a gap in information on steelhead trout.

Priority: It was agreed that the status of salmon in the North Pacific is not well understood and there is a need for collated and standardized data on the status of salmon to be made available. Additionally, there is a need for an atlas and/or other tools to tell the “salmon story” in simple and compelling ways to the informed public and the general public.

Recommendation: Theme Counsel Group for the Status of Salmon and Salmon in a Changing Salmosphere consider convening a workshop on the collation, standardization and communication of data and information on the Status of Salmon.

Gap: Lack of information on the status of Steelhead Trout.

Recommendation: Theme Counsel Group for the Status of Salmon and Salmon in a Changing Salmosphere consider steps required to address the gap.

The “Pacific Salmon and Steelhead Trout in a Changing North Pacific Ocean” topic was thought-provoking, which is not surprising given the title of the workshop. We learned:

- There are a range of approaches being used in the western and eastern North Pacific to link climate and salmon production, and there is a need to synthesize these methods;
- Sea Surface Temperature is the common currency to examine local and regional linkages to a changing environment;
- There is a need to investigate the mechanisms behind linkages to climate indices;
- There is a need to resolve the "critical period hypotheses";
- Impact of competition is a key topic, especially if carrying capacity is reached;
- Year class strength is set at different times depending on the ecosystem;
- That anomalous 2015–2017 conditions are breaking down long standing relationships with ocean and climate indices;
- Continued warming of the North Pacific Ocean will likely affect migration routes and predicted available area for distribution in the future but to what extent?;
- There is improved understanding of chum migration in Japan and Korea;
- Pink/chum/sockeye are migrating into the Arctic and have potential as a sentinel species. An interesting human dimension project is underway to explore the impact of these changes on northern Indigenous Peoples. There is genetic work underway to determine where the sockeye and pink are coming from;
- There is an increasing focus on linking behaviour of individual fish to physiological triggers that are driven by changes in the environment;
- Extreme freshwater events are having significant impacts on fish populations; and
- Algal blooms are affecting salmon populations and we could learn from documenting events across the basin. It is unknown what specifically triggers blooms.

Recommendation: The Theme Counsel Group for Status of Salmon and Salmon in a Changing Salmosphere should consider the following:

- Review Santa Barbara Workshop recommendations for linking climate and salmon—including mechanisms behind shifts in distribution, migration and productivity;
- Develop an approach to address “critical period hypothesis”—linkage to High Seas Ecosystem Signature project;
- Develop an approach to assess carrying capacity of the North Pacific Ocean—linkage to High Seas Ecosystem Signature project;
- Develop an approach to advancing modelling of the behaviour of individual fish;
• Develop an approach to monitoring and understanding the impact of algal blooms and extreme freshwater events; and
• Apply the “Likely Suspects Framework” in the Pacific basin to effectively integrate understanding of the linkages and bottlenecks affecting survival across life history stages.

The third topic covered the remaining three themes New technologies, Management, and Information systems. We learned:

• Forty percent of salmon biomass in the North Pacific are hatchery fish;
• Adaptive hatchery management will be needed in the face of uncertain environments;
• Japan is developing new strategies varying holding methods and time of release;
• Survey indices can effectively predict returns when they survey a life history stage where cohort strength is set and subsequent ecosystems are stable;
• There is a need to incorporate environmental conditions into forecasts;
• There is a need for independent research for steelhead assessments; and
• There is a need to engage fisheries and resource managers in the IYS.

Recommendation: The Theme Counsel Group for New Frontiers and Information Systems should consider the following:

• Convene a workshop on adaptive management in hatcheries in an uncertain environment.

Recommendation: The Theme Counsel Group for the Human Dimensions should consider the following:

• Convene a Salmon Resource management advisory group to engage managers in the development of research that is relevant and helpful to management.

There were several suggestions for improvement of the workshop that organizing committees for subsequent IYS Workshops should consider:

• use web-technology to make sure the broader community of scientists across the hemisphere have an opportunity to learn from these meetings. We publish abstracts from workshops and proceedings from symposia but there are additional ways to engage a broader audience. As a matter of course, we could be webcasting and recording talks so that people can watch them later. Facebook has the capacity to broadcast live and engage audiences if desired. Language is a barrier, but countries could add a translated soundtrack later;
• Each talk should start with a Google Map that zooms into the area of interest for the talk;
• The task of providing a more detailed synthesis of what is learned from each session could be improved by:
  - asking members of the Theme Counsel Groups to draft the synthesis for their related theme/outcome
  - ask presenters to assess in advance the contribution of their work to the research theme/outcome.
## List of Participants

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<tr>
<th>Country</th>
<th>Participants</th>
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<td><strong>Canada</strong></td>
<td>Beacham, Terry</td>
<td>Koval, Maksim</td>
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