CHANGES IN AGE, SIZE AND GROWTH RATE OF THE ANADYR CHUM SALMON *ONCORHYNCHUS KETA* (SALMONIDAE) UNDER CONDITIONS OF GLOBAL WARMING

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The results of the study of annual variability in age composition, body size and growth rate of the Anadyr chum salmon *Oncorhynchus keta* in 2011−2023 revealed that the length and body weight of individuals of all age groups in 2016−2023 significantly decreased compared to the previous period, especially in fish aged 0.4. The proportion of fish of the younger age groups increased. Based on the calculated data, in 2012−2022, the growth rate of chum salmon decreased in the first to second years of life, and multidirectional trends were observed in the third to fourth years, with the lowest increase in the body length in 2016 and 2020. The decrease in the production characteristics of Anadyr chum salmon in the modern period occurred simultaneously with a decrease in the abundance of this salmon species throughout its entire marine range in the North Pacific and depended little on the abundance of other salmon species. The data obtained cast doubt on the leading role of the so-called density factor in determining the production characteristics of fish, which is expressed in food shortages due to an increase in the abundance of Pacific salmon. The abnormally high surface temperatures in the northeast Pacific Ocean over the past seven to eight years have had a marked negative impact on the growth of Anadyr chum salmon.

Keywords: chum salmon, body length, body weight, age, growth rate, global temperature anomaly, Anadyr River.

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INTRODUCTION

In the north-east of Russia, in the largest basin of the Anadyr River, there is a spawning area for the largest chum salmon herd in the region.*Oncorhynchus keta*, which is currently of paramount importance in the economy of the Chukotka Autonomous Okrug and the traditional way of life of the indigenous peoples of Chukotka.

The variability of fish body size and growth, which is determined by a combination of many external (abiotic and biotic) and internal factors of various nature (Chugunova, 1959; Mina, Klevezal, 1976; Dgebuadze, 2001), can serve as an integral characteristic of chum salmon habitat conditions.

Early studies of the long-term dynamics of the size and age of Anadyr chum salmon (1962-2010) showed that the length and body weight of returning spawners change significantly – in the 1990-2000s compared to the 1960-1970s, the size of chum salmon decreased significantly, as did the growth rate after the first year of life, while the age of fish maturation increased (Zavolokin et al., 2012). These changes coincided with a period of increasing salmon abundance in the North Pacific Ocean, leading to assumptions about a deficit of food resources for fish feeding in this area (Ishida et al., 1993; Bigler et al., 1996; Putivkin, 1999; Chereshnev et al., 2002; Makoedov et al., 2009). The results of subsequent long-term studies by Russian specialists (Shuntov, Temnykh, 2008, 2011; Zavolokin, 2015; Shuntov et al., 2017) on determining the state of food supply for Pacific salmon (genus *Oncorhynchus*) in the western North Pacific did not confirm the widespread opinion about the leading role of density factor in the observed decrease in production characteristics of salmon. It was concluded that the key reason for changes in the marine growth of Anadyr chum salmon could be the temperature regime of ocean waters (Zavolokin et al., 2012). However, a number of researchers (Debertin et al., 2017; Ruggerone, Irvine, 2018; Ruggerone et al., 2023) presented an alternative view. They suggested that competition among salmon for prey across vast areas of the North Pacific, primarily dependent on the increasing abundance of pink salmon *O. gorbuscha* , could lead to slower growth and survival, as well as delayed maturation.

Over the past two decades, the World Ocean has significantly warmed (Kennedy et al., 2019; Annual mean temperature change for hemispheres [1]). Along with the long-term steady warming, the frequency of periods of extremely high ocean surface temperatures in certain regions (marine heat waves) has increased, which, due to anthropogenic climate change, will likely become more frequent, more intense, and longer-lasting throughout the 21st century (Frölicher et al., 2018; Oliver et al., 2018). For instance, in the northeastern Pacific Ocean, the most recent marine heat wave lasted for almost three years, from 2019 to 2021, with an intensity of 1.6°C (average sea water temperature anomaly during the event) (Barkhordarian et al., 2022).

These periods of extremely high sea surface temperatures have a serious negative impact on marine organisms and ecosystems (Smale et al., 2019; Laufkotter et al., 2020), and consequently on fisheries in the North Pacific. Here, according to information presented in documents of the North Pacific Anadromous Fish Commission (NPAFC) (http://www.npafc.org/new/pub_documents.html), in the late 2010s - early 2020s, there has been a decline in the abundance (catches) of chum salmon, coho salmon *O. kisutch* and chinook salmon *O. tshawytscha* .

We noticed that in 2020-2023, against the background of declining Anadyr chum salmon numbers, there was also a significant decrease in the size, growth rate, and maturation age of individuals of this species. In this regard, we believe that it is necessary to continue research on the dynamics of chum salmon production indicators and the factors causing them, which is very important for the rational use of salmon stocks.

The purpose of this work is to analyze changes in the size-age structure and interannual growth of Anadyr chum salmon depending on the global temperature anomaly in 2011-2023.

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[1] Annual mean temperature change for hemispheres. GISS Surface Temperature Analysis (v4) (https://data.giss.nasa.gov/gistemp/graphs_v4/. Version 03/2024).

MATERIAL AND METHODS

The work used materials collected in August-September 2011-2023 in the middle reaches of the Anadyr River. Fish were caught with stationary nets and beach seines at permanent sites in the area of the main chum salmon spawning grounds. Each year, 167-290 fish collected throughout the mass salmon run were studied using biological analysis methods (Table 1).

Material processing was carried out in field and laboratory conditions using standard ichthyological methods (Pravdin, 1966). For all fish, we determined the fork length (*FL*), body weight, sex, and age from scales taken above the lateral line at the level of the posterior part of the dorsal fin. To denote the age of fish, we used a system that includes the number of complete freshwater and marine years of life. In addition to age determination, scale processing included measurements of the maximum scale radius and annual zones, with the area of closely spaced circuli considered as the end of each zone (Fig. 1). The final growth zone was defined as the area on the scale from the last annual zone to the edge. Measurements were carried out using the AmScope ToupView 3.1 program on images obtained with a MBS-10 microscope ("LZOS", Russia) and a MU 900 digital camera ("AmScope", China). To determine the rate of marine growth of chum salmon, we calculated the average values of annual increments of individuals aged 0.3 and 0.4 caught in 2016-2023. Growth was analyzed using back-calculation data according to Lea's direct proportionality formula (Lea, 1910 - cited in: Dgebuadze, Chernova, 2009). A total of 418 specimens aged 0.3 and 351 specimens aged 0.4 were studied. In the samples of each year, females and males were present in approximately equal proportions.

Table 1. Length and weight of Anadyr chum salmon *Oncorhynchus keta* in 2011-2023.

Year	Age group, years										Number of fish, specimens
	0.2		0.3		0.4		0.5		All		
	FL, cm	Weight, kg	*FL*, cm	Weight, kg	*FL*, cm	Weight, kg	*FL*, cm	Weight, kg	*FL*, cm	Weight, kg	
2011	— / 56.0	— / 2.00	58.8 ± 0.6 / 63.6 ± 0.8	2.59 ± 0.10 / 3.35 ± 0.14	62.1 ± 0.8 / 69.3 ± 1.0	3.04 ± 0.14 / 4.36 ± 0.20			59.8 ± 0.6 / 65.4 ± 0.8	2.73 ± 0.10 / 3.67 ± 0.16	149 / 138
2012	54.0 / 57.0	1.93 / 2.31	59.5 ± 1.0 / 63.9 ± 1.6	2.63 ± 0.12 / 3.40 ± 0.24	62.5 ± 0.6 / 67.7 ± 0.6	3.06 ± 0.10 / 3.97 ± 0.14	66.7 ± 1.2 / 75.5	3.88 ± 0.35 / 5.55	62.2 ± 0.6 / 67.1 ± 0.6	3.04 ± 0.10 / 3.89 ± 0.14	153 / 126
2013	— / 59.0	— / 2.74	59.3 ± 0.6 / 64.7 ± 0.6	2.74 ± 0.08 / 3.60 ± 0.12	62.1 ± 1.4 / 68.5 ± 1.6	3.19 ± 0.25 / 4.33 ± 0.37	68.0 / 74.3	4.43 / 5.73	59.7 ± 0.6 / 65.0 ± 0.6	2.80 ± 0.08 / 3.66 ± 0.12	144 / 136
2014	55.3 ± 1.2 / 59.2 ± 2.7	2.05 ± 0.15 / 2.54 ± 0.33	59.0 ± 0.8 / 64.5 ± 1.0	2.68 ± 0.12 / 3.45 ± 0.16	62.7 ± 0.6 / 68.4 ± 0.8	3.11 ± 0.12 / 4.20 ± 0.18			60.6 ± 0.6 / 66.4 ± 0.8	2.86 ± 0.10 / 3.82 ± 0.14	160 / 117
2015	56.2 ± 3.3 / 62.7 ± 1.4	1.96 ± 0.39 / 3.26 ± 0.22	59.4 ± 0.6 / 65.1 ± 0.6	2.75 ± 0.10 / 3.71 ± 0.14	63.8 ± 1.2 / 70.4 ± 1.2	3.54 ± 0.18 / 4.86 ± 0.24	— / 73.2	— / 5.78	60.2 ± 0.6 / 66.1 ± 0.6	2.85 ± 0.10 / 3.93 ± 0.14	134 / 152
2016	53.4 ± 0.8 / 57.3 ± 1.4	1.83 ± 0.10 / 2.33 ± 0.18	59.3 ± 0.6 / 64.6 ± 0.8	2.61 ± 0.08 / 3.34 ± 0.12	62.4 ± 0.8 / 68.2 ± 0.8	3.06 ± 0.12 / 4.13 ± 0.16	68.5 / 72.1 ± 2.0	3.94 / 4.95 ± 0.41	59.7 ± 0.6 / 65.5 ± 0.8	2.68 ± 0.08 / 3.60 ± 0.14	169 / 121
2017	53.4 ± 1.4 / 54.7 ± 2.9	1.88 ± 0.22 / 2.09 ± 0.33	58.7 ± 0.6 / 62.8 ± 0.8	2.60 ± 0.10 / 3.25 ± 0.16	61.6 ± 0.8 / 66.0 ± 0.8	3.16 ± 0.12 / 3.94 ± 0.16	66.0 ± 2.0 / 69.9 ± 1.2	3.86 ± 0.45 / 4.85 ± 0.35	59.7 ± 0.6 / 64.4 ± 0.8	2.79 ± 0.10 / 3.62 ± 0.14	132 / 105
2018	53.7 / 60.5	1.79 / 2.38	58.5 ± 0.6 / 61.6 ± 1.0	2.54 ± 0.08 / 3.04 ± 0.22	61.7 ± 0.6 / 65.2 ± 0.6	3.07 ± 0.12 / 3.74 ± 0.14	65.1 ± 1.2 / 70.6 ± 1.2	3.66 ± 0.20 / 4.87 ± 0.31	60.1 ± 0.6 / 65.4 ± 0.8	2.81 ± 0.08 / 3.79 ± 0.16	162 / 102
2019	52.5 / 60.0	1.62 / 2.28	58.8 ± 0.6 / 63.1 ± 0.8	2.61 ± 0.10 / 3.33 ± 0.16	63.1 ± 0.8 / 67.5 ± 1.0	3.35 ± 0.14 / 4.27 ± 0.22	— / 70.6 ± 2.5	— / 5.05 ± 0.45	60.3 ± 0.6 / 65.2 ± 0.8	2.88 ± 0.10 / 3.78 ± 0.16	160 / 107
2020	53.6 ± 1.2 / 55.5 ± 1.0	1.85 ± 0.14 / 2.13 ± 0.14	58.5 ± 0.8 / 63.3 ± 1.0	2.61 ± 0.14 / 3.43 ± 0.18	62.6 ± 1.0 / 65.4 ± 1.6	3.26 ± 0.14 / 3.76 ± 0.33	69.3 /	4.10 /	59.5 ± 1.0 / 61.0 ± 1.2	2.75 ± 0.14 / 3.04 ± 0.20	93 / 74
2021	55.0 ± 2.1 /	2.04 ± 0.30 /	57.4 ± 0.6 /	2.43 ± 0.08 /	61.0 ± 1.4 /	2.96 ± 0.22 /			57.7 ± 0.6 /	2.48 ± 0.08 /	166 / 79

	59.0	2.68	60.6 ± 0.6	2.94 ± 0.12	65.0 ± 1.4	3.66 ± 0.28			61.3 ± 0.8	3.05 ± 0.12	
2022	— / 55.0	— / 1.82	58.8 ± 0.6 / 62.0 ± 1.0	2.58 ± 0.10 / 3.05 ± 0.16	59.2 ± 0.8 / 64.1 ± 0.8	2.62 ± 0.12 / 3.41 ± 0.14			59.0 ± 0.4 / 63.0 ± 0.6	2.60 ± 0.08 / 3.23 ± 0.12	123 / 102
2023			56.9 ± 0.8 / 61.2 ± 0.6	2.38 ± 0.12 / 2.99 ± 0.10	61.5 ± 1.2 / 65.3 ± 1.4	3.12 ± 0.18 / 3.80 ± 0.25	63.5 ± 3.3 / 67.2 ± 2.2	3.60 ± 0.39 / 4.08 ± 0.51	58.2 ± 0.8 / 62.1 ± 0.6	2.59 ± 0.12 / 3.16 ± 0.10	101 / 181

Note. Above the line - indicators (*M* ± 95% confidence interval) for females, below the line - for males. Here and in Table 2: *M* - mean value; here and in Tables 3, 4: *FL* - fork length.

As an indicator of salmon abundance in the North Pacific, we used data on total catch by all countries of the North Pacific basin available on the NPAFC website (http://www.npafc.org/new/pub_documents.html).

The influence of climatic factors on chum salmon growth was assessed using the index of global temperature anomaly in the Northern Hemisphere of the Earth (N.HEMI + dSST), which is calculated based on data from all available meteorological stations, taking into account sea surface temperature reconstruction data as a deviation from the average value for 1951-1980 (Hansen et al., 2010; Annual mean temperature change for hemispheres [1]).

When assessing the annual relationship between fish size and total salmon catch in the North Pacific, a time lag of 2-4 years was considered for chum salmon of corresponding age groups. Statistical processing was performed using Microsoft Excel.

RESULTS

Age structure. Anadyr chum salmon predominantly matures at 3-6 years of age (age 0.2-0.5). In 2011-2023, individuals aged 0.3 and 0.4 traditionally formed the majority of fish returning to spawn. In most years, fish aged 0.3 dominated (44-90%), and only in 2012, 2014, and 2022 did chum salmon aged 0.4 prevail (52-77%). Individuals aged 0.2 were quite numerous in 2016 and

2020 (11% and 23%), and those aged 0.5 – in 2017 and 2018 (8% and 14%). In 2012, the maximum average age of the spawning stock was recorded – 3.9 years (in 2018, the average age was also high – 3.7 years), which is associated with a high proportion of fish aged 0.4 and 0.5, while in 2013, 2020, and 2021, it reached a minimum of 3.1 years (Fig. 2). No significant differences in the dynamics of the age structure between males and females were observed during the period under consideration.

Length and body weight. For Anadyr chum salmon aged 0.3, the average body length from 2011 to 2016 varied slightly from year to year within 58.8-59.5 (annual average 59.2) cm for females and within 63.6-65.1 (64.4) cm for males, while for fish aged 0.4 – 62.1-63.8 (62.6) and 67.7-70.4 (68.8) cm, respectively. Then a noticeable decrease in chum salmon size began, and from 2017 to 2023, the average annual body length of females aged 0.3 was 58.2 cm, males – 62.1 cm, and for fish aged 0.4   61.5 and 65.5 cm, respectively. In 2021, there was a significant sharp decrease in the average length of fish aged 0.3, in 2022 – aged 0.4, and in 2023 – aged 0.5 (Table 1). The body weight of chum salmon changed in a similar manner. In 2011-2016, the largest fish were recorded: the average weight of female chum salmon aged 0.3 was 2.67 kg, males – 3.47 kg, and at age 0.4 – 3.17 and 4.31 kg, respectively. In 2021, the lowest body weight of chum salmon aged 0.3 was observed (2.43 kg for females, 2.94 kg for males), and in 2022 – at age 0.4 (2.62 and 3.41 kg, respectively). For fish aged 0.2, the smallest sizes were recorded in 2016-2017 and in 2020. The trend of declining production indicators of chum salmon in recent years was less pronounced in females than in males of the same age.

The back-calculated body length increments of chum salmon during the study period averaged 25.8, 15.7, 8.6, 6.9 cm for females and 26.1, 16.7, 9.2, 7.5 cm for males. In the first year of life, the growth rate of fish of different sexes did not change significantly. Subsequently, males had higher body length increments, with particularly significant differences observed in the final stage of the marine life period of chum salmon during active pre-spawning migrations (April–July) (Fig. 3). Thus, the average body length increment of females during this life period was 6.3 cm, while for males it was almost 25% greater (8.1 cm). It should also be noted that interannual changes in back-calculated increments for females and males occurred synchronously for all annual zones, therefore for further analysis, these data for fish of different sexes were combined.

In the first year of life, the body length of chum salmon at ages 0.3 and 0.4 did not change significantly until 2016 (average 26.6 cm), then a slight decrease to 25.5 cm was observed (Table 2). The back-calculated body length increments in subsequent years of life averaged 16.6, 9.6 cm for fish at age 0.3 and 15.9, 8.2, 7.1 cm for fish at age 0.4. In the second year of life, the minimum increment for fish of both age groups was observed in 2017, and the maximum – in 2018. In the third and fourth years of life, the lowest growth rates were observed in 2016 and 2020 – annual body length increments for fish at age 0.3 significantly decreased to 8.1 ± 0.4 and 8.7 ± 0.4 cm respectively, and for fish at age 0.4 – to 6.4 ± 0.6 and 6.0 ± 0.8 cm. In the zone of final increment, no trends in changes in the growth rate of chum salmon were observed.

Table 2. Back-calculated annual body length increments (*M* ± 95% confidence interval) of Anadyr chum salmon *Oncorhynchus keta* at ages 0.3 and 0.4 in different periods, cm

Period, years	Annual zone					Number of fish, specimens
	1st	2nd	3rd	4th	Final growth	
Age 0.3						
2013–2016	27.0 ± 0.6	17.9 ± 0.6	9.6 ± 0.6		7.3 ± 0.6	49
2014–2017	26.6 ± 0.6	16.7 ± 0.6	8.1 ± 0.4		8.9 ± 0.8	46
2015–2018	26.4 ± 0.6	16.9 ± 0.6	8.5 ± 0.4		7.9 ± 0.8	38
2016–2019	27.1 ± 0.4	15.5 ± 0.4	11.5 ± 0.4		7.4 ± 0.6	57
2017–2020	25.6 ± 0.6	17.4 ± 0.6	9.8 ± 0.6		8.1 ± 0.8	41
2018–2021	25.4 ± 0.4	17.0 ± 0.4	8.7 ± 0.4		7.9 ± 0.4	80
2019–2022	25.6 ± 0.6	16.1 ± 0.6	10.3 ± 0.4		7.9 ± 0.6	54
2020–2023	25.3 ± 0.4	15.4 ± 0.4	10.2 ± 0.4		7.3 ± 0.6	53
Age 0.4						
2012–2016	26.7 ± 0.4	16.3 ± 0.6	8.7 ± 0.4	7.4 ± 0.6	6.2 ± 0.4	46
2013–2017	26.1 ± 0.6	16.6 ± 0.6	7.7 ± 0.6	6.4 ± 0.6	7.3 ± 0.8	42

2014–2018	26.6 ± 0.6	15.9 ± 0.8	7.5 ± 0.6	7.1 ± 0.6	6.3 ± 0.6	37
2015–2019	25.4 ± 0.6	16.6 ± 0.6	8.8 ± 0.6	8.2 ± 0.4	6.3 ± 0.6	47
2016–2020	27.1 ± 0.8	14.6 ± 0.8	8.8 ± 0.6	6.9 ± 0.6	6.2 ± 0.8	30
2017–2021	25.9 ± 0.6	16.9 ± 0.8	8.3 ± 0.8	6.0 ± 0.8	6.2 ± 0.6	26
2018–2022	25.4 ± 0.4	14.7 ± 0.6	7.5 ± 0.4	7.6 ± 0.4	6.4 ± 0.4	74
2019–2023	25.1 ± 0.6	15.6 ± 0.6	8.6 ± 0.4	7.4 ± 0.4	6.5 ± 0.4	49

DISCUSSION

The Anadyr chum salmon is characterized by a brief freshwater and long marine periods of life. Its wintering, including that of juveniles, occurs predominantly in the eastern and central sectors of Pacific waters south of the Aleutian Islands (Atlas..., 2002). In summer, the fish migrate to the Bering Sea for feeding, which is also an important feeding area for many chum salmon stocks of Asian and American origin (Birman, 1985; Salo, 1991; Ogura, 1994; Shuntov, Temnykh, 2008, 2011; Zavolokin, 2015), and in autumn they return to the ocean. After reaching sexual maturity (mainly at the 4-5th year of life), chum salmon returns to the Anadyr River to spawn.

According to our data, in the last 13 years, the trend of declining production indicators of the Anadyr chum salmon has continued, which has been observed since the 1940s (Chereshnev et al., 2002; Makoedov et al., 2009; Zavolokin et al., 2012). Compared to 1938–1982, the average length of female chum salmon has currently decreased by 3.0 cm, weight by 0.53 kg, and for males by 1.9 cm and 0.59 kg, respectively. A particularly sharp decrease in these indicators occurred in 2020–2023. The average body length of females decreased to 58.6 cm (by 6.7%), weight to 2.60 kg (by 21.2%), and for males to 61.9 cm (by 7.1%) and 3.13 kg (by 25.3%), respectively (Table 3). Also, by the beginning of the 2020s, there was a trend toward an increase in the proportion of younger age groups (0.3 and 0.2) of chum salmon.

Table 3. Biological indicators of Anadyr chum salmon *Oncorhynchus keta* for different observation periods

Years	Sex	*FL* , cm	Weight, kg	Number of fish, specimens	Average age, years
1938–1982	Females	62.8 / 50.0–78.2	3.30 / 1.45–5.85	2346	3.1
	Males	66.6 / 53.5–81.0	4.19 / 1.82–7.56	1873	
1983–2000	Females	61.1 / 47.5–76.0	2.99 / 1.15–6.15	3492	3.4
	Males	66.0 / 51.5–82.0	3.97 / 1.38–7.74	2570	
2001–2010	Females	60.3 / 48.0–72.5	2.86 / 1.18–5.85	2249	3.3
	Males	66.2 / 50.0–80.0	3.94 / 1.52–7.18	1481	
2011–2019	Females	60.3 / 50.0–72.0	2.83 / 1.32–5.09	1372	3.4
	Males	65.7 / 48.5–77.5	3.77 / 1.48–7.13	1159	
2020–2023	Females	58.6 / 49.5–70.0	2.60 / 1.44–4.22	483	3.2
	Males	61.9 / 51.5–73.5	3.13 / 1.59–5.01	436	

Note. Above the line is the mean value, below the line is the range of variation of the indicator. Data for 1938–2000 are taken from the work of Chereshnev et al. (2002); data for 2001–2010 are from the archives of the Ichthyology Laboratory of IBPS FEB RAS.

The results of studies on the interannual dynamics of body size and weight of chum salmon in 2011–2023 show that from 2016 to 2023, both sexes demonstrate a trend of decreasing average length and weight of spawners across all age groups, most pronounced at age 0.4. (Table 1). Additionally, the decrease in size was usually accompanied by a reduction in the age of sexual maturity of chum salmon. Thus, the average age of fish decreased from 3.4 in 2011–2019 to 3.2 in 2020–2023 (Table 3).

According to the calculated body length increments, in 2012–2022, the growth rate in the first and second years of life decreased, while in the third and fourth years, multidirectional trends were observed. All interannual changes in chum salmon increments in the 3-4th years of life occurred synchronously, with the most significant decrease in growth rates in 2016 and 2020 (Fig. 4) – during the last marine heat waves of 2014–2016 and 2019–2021 (Barkhordarian et al., 2022).

Thus, the obtained results indicate that the decrease in the size of Anadyr chum salmon in the second half of the 2010s – early 2020s is associated with a strong slowdown in marine growth in the third and fourth years of fish life.

Recent studies of interannual dynamics of chum salmon body size have revealed that for most populations of this species in various regions of the North Pacific, negative trends in long-term variability of body length and weight were noted from the late 1970s to the 2010s (Fukuwaka et al., 2007, 2009; Kaeriyama et al., 2007; Seo et al., 2009; Temnykh et al., 2011; Zavolokin et al., 2012; Bugaev, 2017; Zavarina, 2020). The decline in chum salmon production indicators is usually associated with the high abundance of salmon observed since the late 1990s. According to many specialists, the so-called density factor, expressed in food shortage and increased food competition, plays a decisive role in this (Ishida et al., 1993; Kishi et al., 2010; Karpenko et al., 2013; Klovach, Elnikov, 2013; Ruggerone, Irvine, 2018; Ruggerone et al., 2023).

According to our data, in 2011-2023, on the contrary, there was a positive correlation between fish size and total chum salmon catch (Table 4) and a weak negative correlation with pink salmon catch in the North Pacific ($r = -0.19$–0.21). Additionally, according to ChukotNIO data, in the early 2020s, the abundance of these salmon species in the Anadyr basin also significantly decreased. It is important to add that Asian pink salmon in all rivers of the mainland coast of the Bering Sea is relatively scarce, and salmon hatchery production in the region is completely absent. This suggests that the density factor cannot be the primary cause of the observed decrease in production characteristics of Anadyr chum salmon.

Table 4. Pearson correlation coefficients between the total catch of chum salmon *Oncorhynchus keta* in the North Pacific and body size of Anadyr chum salmon in 2011-2023.

Age, years	*FL*		Weight	
	r	*p*	*r*	*p*
0.2	0.39	0.21	0.43	0.17
0.3	0.83	<0.001	0.74	<0.01
0.4	0.76	<0.01	0.65	<0.05

Note. Here and in Table 5: *r* - correlation coefficient, *p* - probability value.

The influence of climatic factors, which largely determine the hydrochemical and temperature characteristics of fish habitats, on salmon growth is undoubted. Recent research results assessing the impact of climate variability on the productivity of Pacific salmon have made it possible to identify the most significant temperature parameter - the N.HEMI + dSST index, which is a universal indicator of overall climate change relative to the long-term average trend (Myers et al., 2007; Zavolokin et al., 2012; Bugaev, 2017; Bugaev et al., 2018, 2021). The interannual dynamics of this index showed that since the late 1980s, there has been a noticeable upward trend, and in the last 10 years, there have been two significant jumps in air temperature and surface oceanic waters in the North Pacific (in 2016 and 2020), i.e., directly in the feeding and wintering zone of Pacific salmon. To assess the impact of the observed temperature anomalies on fish growth, we compared the calculated average length increments of Anadyr chum salmon and the variability of the N.HEMI + dSST index in 2012-2022. In the first and second years of fish life, there was a slight decrease in their growth after 2016, while in the third and fourth years, a synchronous inverse relationship between annual increments and changes in the temperature anomaly index was observed (Fig. 4). Correlation analysis showed the presence of a moderately high negative relationship (Table 5). In addition, it was found that the total catch of Pacific chum salmon also negatively correlates with this index ($r = -0.80$, $p < 0.01$).

Table 5. Pearson correlation coefficients between the calculated body length increments of Anadyr chum salmon *Oncorhynchus keta* and the climate index of global temperature anomaly in the Northern Hemisphere of the Earth (N.HEMI + dSST) in 2012-2023.

Age, years	Annual zone									
	1st		2nd		3rd		4th		Final growth	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
0.3	−0.38	0.35	−0.50	0.21	−0.84	<0.01			−0.21	0.65
0.4	−0.21	0.61	−0.40	0.33	−0.78	<0.05	−0.98	<0.001	−0.20	0.67

Thus, the significant acceleration in the rate of global warming over the past seven to eight years, identified by the temperature anomaly in the Northern Hemisphere of the Earth, has had a noticeable negative impact on the growth of Anadyr chum salmon. Note that the greatest changes in growth coincided with recent severe marine heat waves in 2014-2016 and 2019-2021 in the northeastern Pacific Ocean. It is known that such periods of extremely high regional ocean surface temperatures can alter the structure and functioning of entire marine ecosystems, causing mass mortality, shifts in species ranges, and community reorganizations (Smale et al., 2019). In the future, this may cause additional problems in salmon fisheries management, as climate change pushes species toward the poles and reduces the productivity of some species' stocks (Cheung, Frölicher, 2020).

CONCLUSION

The age composition of Anadyr chum salmon during the period under review included individuals aged 0.2-0.5. The majority of returning spawners (>80%) consisted of fish aged 0.3 and 0.4. In the early 2020s, there was a trend toward an increasing proportion of fish from younger age groups (0.3 and 0.2).

The body length and weight of female and male chum salmon of all age groups significantly decreased from 2016 to 2023 compared to the previous period, especially in fish aged 0.4. During different years of life in 2012-2022, the growth of Anadyr chum salmon varied unequally. Growth rates in the first and second years of life decreased slightly, while in the third and fourth years, a significant slowdown was observed in 2016 and 2020.

The decrease in chum salmon production rates in the modern period occurred simultaneously with a decrease in the abundance of this salmon species throughout its marine range in the North Pacific and was little dependent on the abundance of other salmon species. This calls into question the leading role of the so-called density factor in determining the production characteristics of fish, expressed in food shortages due to the increasing numbers of Pacific salmon.

Abnormally high surface temperatures in the northeastern part of the Pacific Ocean observed in the last seven to eight years have had a significant negative impact on the growth of the Anadyr chum salmon. Additionally, in 2016 and 2020, there was a reduction in the duration of marine and oceanic feeding of fish, caused by earlier sexual maturation, which may be a specific response to the increasing temperature anomaly. Underestimating the relationship between water temperature regimes and changes in production characteristics of regional chum salmon populations may lead to incorrect forecasting of stock dynamics and additional problems in salmon fishery management.

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COMPLIANCE WITH ETHICAL STANDARDS

The collection of material and its processing complied with international standards for the treatment of animals, in accordance with Directive 2010/63/EU of the European Parliament and of the Council of the European Union dated 22.09.2010 on the protection of animals used for scientific purposes (https://ruslasa.ru/wp-content/uploads/2017/06/Directive_201063_rus.pdf).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflict of interest.

REFERENCES

Atlas of distribution of various stocks of Pacific salmon in the sea during the spring-summer feeding and pre-spawning migrations. 2002. Moscow: VNIRO Publishing House, 190 p.

Birman I.B. 1985. Marine period of life and issues of Pacific salmon stock dynamics. Moscow: Agropromizdat, 208 p.

Bugaev A.V. 2017. Assessment of the impact of stock abundance and global temperature anomaly on the average body weight of Pacific salmon in the North Pacific basin // Izv. TINRO. Vol. 191. P. 3-33. https://doi.org/10.26428/1606-9919-2017-191-3-33

Bugaev A.V., Tepnin O.B., Radchenko V.I. 2018. Climatic variability and productivity of Pacific salmon in the Russian Far East // Research of aquatic biological resources of Kamchatka and the northwestern Pacific Ocean. Issue 49. P. 5-50. https://doi.org/10.15853/2072-8212.2018.49.5-50

Bugaev A.V., Feldman M.G., Tepnin O.B., Koval M.V. 2021. Water surface temperature anomalies in the western North Pacific as a potential climate predictor for forecasting the abundance of Pacific salmon in Kamchatka // Vopr. rybolovstva. Vol. 22. No. 4. P. 46–62. https://doi.org/10.36038/0234-2774-2021-22-4-46-62

Dgebuadze Yu.Yu. 2001. Ecological patterns of fish growth variability. Moscow: Nauka, 276 p.

Dgebuadze Yu.Yu., Chernova O.F. 2009. Scales of bony fishes as a diagnostic and recording structure. Moscow: KMK Scientific Press, 315 p.

Zavarina L.O. 2020. Assessment of spawning runs, fishery and biological state of chum salmon (*Oncorhynchus keta*) in the Bolshaya Vorovskaya River basin (Western Kamchatka) in the modern period (2011–2019) // Research of aquatic biological resources of Kamchatka and northwestern Pacific Ocean. Issue 58. P. 42–50. https://doi.org/10.15853/2072-8212.2020.57.42-50

Zavolokin A.V. 2015. Food supply of Pacific salmon during marine and oceanic feeding: Abstract of doctoral dissertation in biological sciences. Vladivostok: TINRO-Center, 48 p.

Zavolokin A.V., Kulik V.V., Glebov I.I. et al. 2012. Dynamics of size, age and intra-annual growth rates of Anadyr chum salmon *Oncorhynchus keta* in 1962–2010 // Journal of Ichthyology. Vol. 52. No. 2. P. 215–233.

Karpenko V.I., Andrievskaya L.D., Koval M.V. 2013. Feeding and growth characteristics of Pacific salmon in marine waters. Petropavlovsk-Kamchatsky: KamchatNIRO Publishing, 303 p.

Klovach N.V., Elnikov A.N. 2013. Structure of the spawning stock of chum salmon *Oncorhynchus keta* in the Olyutorsky Gulf of the Bering Sea (Northeastern Kamchatka) // Journal of Ichthyology. Vol. 53. No. 6. P. 707–717. https://doi.org/10.7868/S0042875213060040

Makoedov A.N., Korotaev Yu.A., Antonov N.P. 2009. Asian chum salmon. Petropavlovsk-Kamchatsky: KamchatNIRO Publishing, 356 p.

Mina M.V., Klevezal G.A. 1976. Animal growth. Moscow: Nauka, 291 p.

Pravdin I.F. 1966. Guide to the study of fish. Moscow: Food Industry, 376 p.

Putivkin S.V. 1999. Biology and population dynamics of Anadyr chum salmon: Abstract of PhD dissertation in biological sciences. Vladivostok: TINRO-Center, 24 p.

Temnykh O.S., Zavolokin A.V., Shevlyakov E.A. et al. 2011. Features of interannual variability of average sizes and age composition of chum salmon from Russian stocks // Bull. No. 6 studying Pacific salmon in the Far East. P. 228–241.

Chereshnev I.A., Volobuev V.V., Shestakov A.V., Frolov S.V. 2002. Salmonid fishes of the North-East of Russia. Vladivostok: Dalnauka, 496 p.

Chugunova N.I. 1959. Guide to studying the age and growth of fish. Moscow: USSR Academy of Sciences Publishing House, 164 p.

Shuntov V.P., Temnykh O.S. 2008. Pacific salmon in marine and oceanic ecosystems. Vol. 1. Vladivostok: TINRO-Center Publishing House, 481 p.

Shuntov V.P., Temnykh O.S. 2011. Pacific salmon in marine and oceanic ecosystems. Vol. 2. Vladivostok: TINRO-Center Publishing House, 473 p.

Shuntov V.P., Temnykh O.S., Ivanov O.A. 2017. On the stability of stereotypes in concepts of marine ecology of Pacific salmon *Oncorhynchus* spp. // Izv. TINRO. Vol. 188. P. 3–36.

Barkhordarian A., Nielsen D.M., Baehr J. 2022. Recent marine heatwaves in the North Pacific warming pool can be attributed to rising atmospheric levels of greenhouse gases // Commun. Earth Environ. V. 3. Article 131. https://doi.org/10.1038/s43247-022-00461-2

Bigler B.S., Welch D.W., Helle J.H. 1996. A review of size trends among North Pacific salmon *Oncorhynchus* spp. // Can. J. Fish. Aquat. Sci. V. 53. № 2. P. 455–465. https://doi.org/10.1139/f95-181

Cheung W.W.L., Frölicher T.L. 2020. Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific // Sci. Rep. V. 10. Article 6678. https://doi.org/10.1038/s41598-020-63650-z

Debertin A.J., Irvine J.R., Holt C.A. et al. 2017. Marine growth patterns of southern British Columbia chum salmon explained by interactions between density-dependent competition and changing climate // Can. J. Fish. Aquat. Sci. V. 74. № 7. P. 1077–1087. https://doi.org/10.1139/cjfas-2016-0265

Frölicher T.L., Fischer E.M., Gruber N. 2018. Marine heatwaves under global warming // Nature. V. 560. № 7718. P. 360–364. https://doi.org/10.1038/s41586-018-0383-9

Fukuwaka M., Azumaya T., Nagasawa T. et al. 2007. Trends in abundance and biological characteristics of chum salmon // NPAFC Bull. V. 4. P. 35–43.

Fukuwaka M., Davis N.D., Azumaya T., Nagasawa T. 2009. Bias-corrected size trends in chum salmon in the central Bering Sea and North Pacific Ocean // Ibid. V. 5. P. 173–176.

Hansen J., Ruedy R., Sato M., Lo K. 2010. Global surface temperature change // Rev. Geophys. V 48. № 4. Article RG4004. https://doi.org/10.1029/2010RG000345

Ishida Y., Ito S., Kaeriyama M. et al. 1993. Resent changes in age and size of chum salmon (*Oncorhynchus keta*) in the North Pacific Ocean and possible causes // Can. J. Fish. Aquat. Sci. V. 50. № 2. P. 290–295. https://doi.org/10.1139/f93-033

Kaeriyama M., Yatsu A., Noto M., Saitoh S. 2007. Spatial and temporal changes in the growth patterns and survival of Hokkaido chum salmon populations in 1970–2001 // NPAFC Bull. V. 4. P. 251–256.

Kennedy J.J., Rayner N.A., Atkinson C.P., Killick R.E. 2019. An ensemble data set of sea surface temperature change from 1850: the Met Office Hadley Centre HadSST.4.0.0.0 data set // J. Geophys. Res. Atmos. V. 124. № 14. P. 7719–7763. https://doi.org/10.1029/2018JD029867

Kishi M.J., Kaeriyama M., Ueno H., Kamezawa Y. 2010. The effect of climate change on the growth of Japanese chum salmon (*Oncorhynchus keta*) using a bioenergetics model coupled with a three-dimensional lower trophic ecosystem model (NEMURO) // Deep Sea Res. Pt. II. Top. Stud. Oceanogr. V. 57. № 13–14. P. 1257–1265. https://doi.org/10.1016/j.dsr2.2009.12.013

Laufkotter C., Zscheischler J., Frolicher T.L. 2020. High-impact marine heatwaves attributable to human-induced global warming // Science. V. 369. № 6511. P. 1621–1625. https://doi.org/10.1126/science.aba0690

Myers K.W., Klovach N.V., Gritsenko O.F. et al. 2007. Stock-specific distributions of Asian and North American salmon in the open ocean, interannual changes, and oceanographic conditions // NPAFC Bull. V. 4. P. 159–177.

Ogura M. 1994. Migratory behavior of Pacific salmon (*Oncorhynchus* sp.) in the open sea // Bull. Natl. Res. Inst. Far Seas Fish. V. 31. P. 1–141.

Oliver E.C.J., Donat M.G., Burrows M.T. et al. 2018. Longer and more frequent marine heatwaves over the past century // Nat. Commun. V. 9. Article 1324. https://doi.org/10.1038/s41467-018-03732-9

Ruggerone G.T., Irvine J.R. 2018. Numbers and biomass of natural- and hatchery-origin pink salmon, chum salmon, and sockeye salmon in the North Pacific Ocean, 1925–2015 // Mar. Coast. Fish. V. 10. № 2. P. 152–168. https://doi.org/10.1002/mcf2.10023

Ruggerone G.T., Springer A.M., van Vliet G.B. et al. 2023. From diatoms to killer whales: impacts of pink salmon on North Pacific ecosystems // Mar. Ecol. Prog. Ser. V. 719. P. 1–40. https://doi.org/10.3354/meps14402

Salo E.O. 1991. Life history of Chum Salmon (*Oncorhynchus keta*) // Pacific salmon life histories. Vancouver: UBC Press. P. 231–310.

Seo H., Kudo H., Kaeriyama M. 2009. Spatiotemporal change in growth of two populations of Asian chum salmon in relation to intraspecific interaction // Fish. Sci. V. 75. № 4. P. 957–966. https://doi.org/10.1007/s12562-009-0126-9

Smale D.A., Wernberg T., Oliver E.C.J. et al. 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services // Nat. Clim. Chang. V. 9. № 4. P. 306–312. https://doi.org/10.1038/s41558-019-0412-1

FIGURE CAPTIONS

Fig. 1. Scales of the Anadyr chum salmon *Oncorhynchus keta* : a – female *FL* 51.0 cm, age 0.3; b – male *FL* 55.5 cm, age 0.3; c – female *FL* 55.4 cm, age 0.4; d – male *FL* 60.0 cm, age 0.4. *R* – maximum scale radius; *1 – 4* – radii of the corresponding annual zones.

Fig. 2. Age composition of the Anadyr chum salmon *Oncorhynchus keta* in catches from 2011-2023:
(▤) – 0.2, (■) – 0.3, (□) – 0.4, (▦) – 0.5. (– ● –) – average age.

Fig. 3. Linear growth rate of the Anadyr chum salmon *Oncorhynchus keta* based on back-calculated data in 2012-2023: (--♦--) – females, (··●··) – males. Here and in Fig. 4: (⌶) – 95% confidence intervals.

Fig. 4. Interannual changes in back-calculated body length increments of the Anadyr chum salmon *Oncorhynchus keta* at ages 0.3 and 0.4 (a) and the global temperature anomaly index in the Northern Hemisphere of Earth (N.HEMI + dSST) (b) in 2012-2022.