Marine-entry timing and growth rates of juvenile Chum Salmon in Alaskan waters of the Chukchi and northern Bering seas

Stacy L. Vega[a*], Trent M. Sutton[a], and James M. Murphy[b]

[a]University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, 905 N. Koyukuk Drive, 245 O'Neill Building, Fairbanks, AK 99775-7220, USA; +1 (626) 710-7711; stacylvega@gmail.com

[a]University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, 905 N. Koyukuk Drive, 245 O'Neill Building, Fairbanks, AK 99775-7220, USA; +1 (907) 474-7285; tmsutton@alaska.edu

[b] Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 17109 Point Lena Loop Road, Juneau, AK 99801, USA; +1 (907) 789-6651; jim.murphy@noaa.gov

*Corresponding author

1   **Abstract**

2   Climate change in the Arctic has implications for influences on juvenile Chum Salmon

3   *Oncorhynchus keta* early life-history patterns, such as altered timing of marine entry and/or early

4   marine growth. Sagittal otoliths were used to estimate marine entry dates and daily growth rates

5   of juvenile Chum Salmon collected during surface trawl surveys in summers 2007, 2012, and

6   2013 in the Chukchi and northern Bering seas. Inductively coupled plasma-mass spectrometry

7   (ICP-MS) was used to discriminate between freshwater and marine sagittal growth on the

8   otoliths, and daily growth increments were counted to determine marine-entry dates and growth

9   rates to make temporal and regional comparisons of juvenile Chum Salmon characteristics.

10   Marine-entry dates ranged from mid-June to mid-July, with all region and year combinations

11   exhibiting similar characteristics in entry timing (i.e. larger individuals at the time of capture

12   entered the marine environment earlier in the growing season than smaller individuals in the

13   same region/year), as well as similar mean marine-entry dates. Juvenile Chum Salmon growth

14   rates were on average 4.9% body weight per day in both regions in summers 2007 and 2012, and

15   significantly higher (6.8% body weight per day) in the Chukchi Sea in 2013. These results

16   suggest that juvenile Chum Salmon in the northern Bering and Chukchi seas currently exhibit

17   consistent marine-entry timing and early marine growth rates, despite some differences in

18   environmental conditions between regions and among years. This study also provides a baseline

19   of early marine life-history characteristics of Chum Salmon for comparisons with future climate

20   change studies in these regions.

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1. Introduction

Pacific salmon *Oncorhynchus* spp. in the northern Bering and Chukchi seas may be affected by changing oceanographic conditions due to warming trends in the Arctic and sub-Arctic (Sigler et al. 2011; Nielsen et al. 2013). Climate-change predictions include warmer temperatures at higher latitudes, hydrographic changes for salmon-bearing streams, and rising sea surface temperatures (SSTs; Crozier et al. 2008). Future changes in climate may cause fish populations to exhibit shifts in response to ecological changes (Walther et al. 2002), which includes range extensions, altered timing of spawning runs, and modifications to ecology and of life-history stage dynamics (Nielsen et al. 2013). These changes have implications on the distribution and abundance of Chum Salmon in the northern Bering and Chukchi seas, which are an important commercial, subsistence, and recreational resource throughout Alaska. In the Arctic-Yukon-Kuskokwim (AYK) area which drains into the Bering, Chukchi, and Beaufort seas, commercial harvests of Chum Salmon totaled over one million fish in 2012 (Eggers et al. 2013). Subsistence harvest of Chum Salmon is commonly the primary salmon resource available in these western and northwestern Alaska drainages, with average catches in the Yukon and Kuskokwim River drainages between 60,000 and 100,000 fish per year since the 1990s (Wolfe and Spaeder 2009; Brown and Jallen 2012; Ikuta 2012).

The first summer spent in the ocean is a critical period for growth and survival of Pacific salmon. The timing of outmigration is important for juvenile salmon so that they reach the marine environment when food resources are available for optimal growth and survival (Mueter et al. 2005; Quinn 2005). Juvenile salmon that do not reach a critical size during their first summer at sea may not survive due to size-dependent mortality (Beamish and Mahnken 2001) or the harsh metabolic demands of winter (Farley et al. 2009). Larger individuals are more likely to

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45 survive periods of starvation due to higher energy reserves than smaller fish, typically have

46 greater tolerance to environmental variability, and are less vulnerable to predation (Sogard 1997;

47 Beamish et al. 2004). As a result, year-class strength has been shown to be directly related to

48 growth during the first marine year (Sogard 1997; Beamish et al. 2004).

49   Environmental diversity and behaviors exhibited by Pacific salmon allows for the

50 alteration of life-history in response to climate change, including juvenile migration timing and

51 early marine growth rates (Crozier et al. 2008). Therefore, there is a clear need to understand the

52 early marine period of Pacific salmon life histories in the northern Bering and Chukchi Seas.

53 Both regions are important for the feeding, growth, and survival of juvenile Chum Salmon from

54 western Alaska watersheds (Farley and Moss 2009; Moss et al. 2009a; Sigler et al. 2011).

55 However, the Chukchi Sea is a data-poor region which has been minimally studied with respect

56 to juvenile salmon ecology. By understanding the full range of juvenile Chum Salmon early life-

57 history characteristics and growth information at a regional scale, managers will be better

58 equipped to make predictions on climate change effects. The objectives of this study were to

59 compare the timing of marine entry and early marine growth rate of juvenile Chum Salmon in

60 the northern Bering and Chukchi seas. This research provides a baseline on the status of juvenile

61 Chum Salmon in the northern Bering and Chukchi seas, and is a benchmark for future

62 comparisons that result from a changing Arctic climate.

63 **2. Materials and Methods**

64 *2.1 Fish collection*

65   Juvenile Chum Salmon were collected during the U.S. Bering-Aleutian Salmon

66 International Survey (BASIS) from September 5-September 13, 2007 in the Chukchi Sea (CS)

67 and September 14-September 20, 2007 in the northern Bering Sea (NBS) onboard the NOAA

68   ship *Oscar Dyson*. Sampling continued in the NBS from September 17-October 3, 2007 onboard

69   the F/V *Sea Storm.* During the Arctic Ecosystem Integrated Survey (Arctic Eis), trawls were

70   conducted onboard the *F/V Bristol Explorer* from August 7-September 8, 2012/2013 in the CS

71   and from September 10-September 25, 2012/2013 in the NBS. A Cantrawl model 400/601

72   (Cantrawl Pacific Limited, Richmond, British Columbia) midwater hexagonal mesh trawl (198

73   m long, with a 50-m horizontal opening and a 120-m headrope; 12-mm mesh cod-end liner) was

74   used to sample to a depth of 20 m. Sampling stations were spaced at 55-km intervals along

75   latitudinal and longitudinal lines in the CS (66° N-70° N) and NBS (60° N-65.5^o N) east of -170°

76   W longitude (Figure 1; see Figure 2 in Moss et al. 2009a).

77   During the trawl surveys, juvenile salmon were sorted by species and subsamples of each

78   species were measured for fork length (FL) to the nearest 1 mm and wet weight to the nearest 1

79   g. If more than 50 juvenile Chum Salmon were caught in a trawl haul, a random subsample of 50

80   fish across all measured sizes was selected for biological sampling. Samples from the NBS in

81   2013 were not included in these analyses due to a flooding event onboard the F/V *Bristol*

82   *Explorer* which resulted in the loss of all samples collected from this region. To evaluate marine-

83   entry timing and growth rates of juvenile Chum Salmon, a subsampling approach was used to

84   select otolith samples from the CS and NBS. Fish were organized into 20-mm FL-frequency bins

85   and all samples were used from FL-frequency bins with fewer than 10 samples. For consistency

86   in sample size across regions and years, samples were chosen at random from all remaining FL-

87   frequency bins and across stations until the total sample size reached between 100 to 110 fish. In

88   the CS in 2012 and 2013, all samples were used for analyses due to low catches.

89   *2.2 Otolith preparation*

90   Left sagittal otoliths of juvenile Chum Salmon were mounted on microscope slides with

91   Crystalbond™ thermoplastic resin mounting adhesive (Structure Probe, Inc., West Chester,

92   Pennsylvania). Otoliths were thin sectioned along the sagittal plane using a Histolic Precision

93   Grinding Fixture (Buehler Ltd., Lake Bluff, Illinois) and hand-ground on wet 5-μm lapping film

94   (Precision Surfaces International, Houston, Texas) until daily growth increments were visible.

95   Just prior to reaching the core, the microscope slide was reheated and the otolith was turned over

96   to polish the second side until the core and daily growth increments could be observed using a

97   Leica compound microscope (Leica Microsystems, Wetzlar, Germany) with transmitted light.

98   Preparation of otoliths from the NBS in 2007 differed slightly from the other four

99   sampling region/year combinations. These samples were prepared at the NOAA facilities in

100   Juneau, Alaska, and polished by hand on a LaboPol-21 polishing machine (Struers, Inc.,

101   Cleveland Ohio) using 1200 and 4000 grit wet-dry sandpaper under flowing water (Murphy et al.

102   2009). Batch slides of otoliths were created, leveled using a digital micrometer to a uniform

103   thickness, and briefly polished with 8000 grit micro-mesh polishing cloth (Murphy et al. 2009).

104   All other facets of preparation were identical to procedures followed for 2012 and 2013 samples.

105   *2.3 ICP-MS*

106   Otolith chemical analyses were completed using an Agilent 7500ce inductively-coupled

107   plasma mass spectrometer (ICP-MS; Agilent Technologies, Inc. Santa Clara, California) fitted

108   with a "cs" lens stack and coupled with a New Wave UP213 laser ablation system (New Wave

109   Research, Fremont, California) at the Advanced Instrumentation Laboratory (AIL), University of

110   Alaska Fairbanks. A "cs" lens stack has a larger set of apertures for ions to enter and increases

111   sensitivity and allows for lower limits of detection compared to the default "ce" lens stack. All

112   ablations occurred in a helium atmosphere and a NIST 610 (Ca^{43}) standard reference material

113   was used as a calibration standard. Raw data were processed and calibrated with the Iolite

114   software package (Melbourne Iolite Group, Melbourne, Australia; Paton et al. 2011) using the

115   method described in Longerich et al. (1996).

116   Ablations took place on a transverse cross-section from the ventral to the dorsal side of

117   the otolith passing through the core. The chemical cores of otoliths were identified by a peak in

118   the molar ratio of manganese to calcium (Mn:Ca). A sharp increase in otolith strontium

119   concentration along the molar ratio transect gave a chemical reference point for marine entry.

120   Although there is variation in the magnitude of strontium to calcium molar ratios (Sr:Ca) among

121   different aquatic systems (Zimmerman 2005; Arai and Hirata 2006), the use of these ratios gives

122   sufficient discrimination to distinguish between freshwater, brackish water, and seawater for the

123   different life-history stages of diadromous fishes (Walther and Limberg 2012). To identify a

124   marine-entry point on the otolith, the chemical reference points from Sr:Ca and Mn:Ca molar

125   ratio plots were overlain onto the sectioned otolith images and inspected to identify the visual

126   patterns that corresponded to the transition (low to high) in Sr:Ca molar ratios, from here on

127   called the "smolt check". Otolith chemistry using ICP-MS was used as a validation for the

128   marine-entry point on the otolith, and a subsample of 20-22 otoliths (82 total) from the entire FL

129   range for each region and year combination were used to establish the accuracy of estimating

130   ocean entry using growth checks (Table 1). Samples from 2007 NBS were the exception to this

131   subsampling approach, where Murphy et al. (2009) used all 112 prepared otoliths for chemical

132   analysis using the ICP-MS (Table 1).

133   *2.4 Juvenile Chum Salmon marine-entry timing*

134   Growth increments on juvenile Chum Salmon otoliths were assumed to be deposited

135   daily (see Saito et al. 2007). Two independent readers used Image Pro Plus software (Version

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136 7.0, Media Cybernetics Inc., Rockville, Maryland) to count daily increments from the otolith

137 edge to the beginning of the smolt check. If there was not agreement between readers, a concert

138 read was conducted by both individuals and an agreement was reached. Between 51- 63% of the

139 prepared otoliths had an identifiable smolt check, but did not yield clear and countable daily

140 growth increments. For those samples, an average number of daily growth increments was used

141 where this average was based on the region-year combination of the unreadable otolith. All data

142 analyses were conducted with and without these samples, and there was no significant difference

143 in results when the otoliths with unreadable smolt checks were left out of the sample set. The

144 date of marine entry for each fish was calculated by subtracting the total number of daily

145 increments, which included the smolt check, from the date of fish capture.

146 *2.5 Juvenile Chum Salmon growth rates*

147 Growth rates of juvenile Chum Salmon among regions were determined from slope

148 coefficients of the length-at-age linear regression and weight-at-age exponential growth model.

149 Linear growth was modeled as:

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$$l_i = \beta x_i + \alpha,$$

151 where l_i was the FL in mm, parameter β was the slope, or relative growth rate, x_i was the age in

152 days of the *i*th fish, and parameter α was the intercept. Exponential growth was modeled as:

153
$$w_i = \alpha e^{\beta x_i},$$

154 where w_i was the wet fish weight in g, parameter α was the intercept, e was a mathematical

155 constant (natural log base), x_i was the age in days of the *i*th fish, and parameter β was the slope,

156 or relative growth rate, used as an estimate of growth in weight per day (wt/d). Relative growth

157 rate was converted to percent body weight per day (%/d) when multiplied by 100 (Murphy et al.

158 2009).

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159 **3. Results**

160   During 2007, juvenile Chum Salmon were caught at 20 stations in the CS (n = 292) and

161 36 stations in the NBS (n = 559). Only three stations yielded juvenile Chum Salmon in the CS in

162 2012 (n = 104) and 2013 (n = 95), whereas juvenile Chum Salmon were captured at 16 stations

163 in the NBS in 2012 (n = 480). The size of juvenile Chum Salmon collected within the CS during

164 2007 ranged from 135 to 220 mm FL and 20 to 126 g; size of juvenile Chum Salmon collected in

165 the NBS ranged from 141 to 252 mm FL and 30 to 187 g (Table 2). In 2012 and 2013, juvenile

166 Chum Salmon collected from the CS ranged from 90 to 160 mm FL and 6 to 40 g in weight,

167 whereas juveniles from the NBS ranged from 120 to 217 mm FL and 16 to 104 g in weight in

168 2012 (Table 2).

169 *3.1 Juvenile Chum Salmon marine-entry timing*

170   The timing of entry to the marine environment for juvenile Chum Salmon ranged from

171 mid-June to mid-July among regions and years (Table 2). Fish captured earlier in the year

172 (2012/2013 CS) were smaller in FL and had fewer marine increments than fish captured later in

173 the year (CS 2007, NBS 2007, and NBS 2012; Table 2). Smaller fish at the time of capture

174 entered the marine environment later in the growing season than larger individuals (i.e. mean

175 marine otolith increments were fewer for smaller fish (Table 2)). Larger fish had more daily

176 marine increments, with differences between the largest and smallest (FL) individuals in each

177 region/year combination ranging from 12 to 23 increments, or 12 to 23 days (Table 2). The

178 standard deviations of mean entry dates increased with both fish size and sample size in each

179 length bin (Table 2). Mean marine entry dates between each region/year were significantly

180 different (ANOVA, F = 17.65, P < 0.001). A Tukey's HSD (honest significant difference)

181 multiple comparisons test determined that juvenile Chum Salmon from the CS in 2007 had the

182 earliest mean entry date (Table 2), which was significantly earlier than the other region/year

183 combinations (June 26, d 177; P < 0.05), with the exception of juvenile Chum Salmon from the

184 CS in 2013. The mean entry date of juvenile Chum Salmon from the NBS in 2012 was the latest

185 (Table 2) and was significantly later than of all region/year combinations (July 1, d 183; P <

186 0.05).

187 *3.2 Juvenile Chum Salmon growth rates*

188 Growth rates of juvenile Chum Salmon in length-at-age and weight-at-age showed

189 similar characteristics across regions and years. Length-at-age did not differ significantly among

190 sampled regions and years (ANCOVA, F = 1.29, P = 0.272; Figure 2). Slope coefficients of

191 linear models of length-at-age showed growth rates of 2.31mm/d, 2.47 mm/d, 2.60 mm/d, 2.82

192 mm/d, and 2.41 mm/d for CS 2007, CS 2012, CS 2013, NBS 2007, and NBS 2012, respectively,

193 with an overall average of 2.52mm/d (Figure 2). Differences in weight-at-age were detected

194 among regions and years (ANCOVA, F = 345.2, P < 0.001; Figure 3). Exponential growth

195 models of weight-at-age showed that growth rates of juvenile Chum Salmon were 4.18%/d,

196 5.34%/d, 6.77%/d, 4.96%/d, and 4.88%/d for CS 2007, CS 2012, CS 2013, NBS 2007, and NBS

197 2012, respectively, with an overall average of 5.23%/d (Figure 3). Only juvenile Chum Salmon

198 weight-at-age growth rates from the CS in 2013 were significantly different from the other

199 region/year combinations (F = 8.2, P = 0.005; Figure 3). Growth rates from all other region/year

200 combinations were not significantly different from each other (P > 0.05).

201 **4. Discussion**

202 Early marine life-history patterns of Chum Salmon are important features in their overall

203 strategy for survival (Beamish et al. 2004; Farley et al. 2009; Tomaro et al. 2012). Marine-entry

204 timing of juvenile Chum Salmon was similar among the three years and between the two regions

205 sampled in this study, and early marine growth rates had significant differences. Timing of

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206   marine entry occurred consistently between mid-June and mid-July, and fish exhibited similar

207   characteristics in marine-entry timing in both regions. Our analyses suggest that the larger Chum

208   Salmon that were captured in the northern Bering Sea (NBS) and Chukchi Sea (CS) entered the

209   marine environment earlier in the growing period (i.e. had an earlier timing of marine entry) than

210   smaller individuals. This outcome (i.e. larger body size) was likely due to earlier outmigrants

211   having a longer time to feed and grow in the marine environment relative to smaller fish which

212   entered marine waters later in the growing season. Growth rate estimates were consistently 4-5%

213   of body weight per day (%/d), with the exception of the CS in summer 2013 which had a higher

214   growth rate (6.8%/d) than the other region/year combinations. These early marine life-history

215   stage attributes of Chum Salmon have the potential to be affected by climate change in these

216   regions of the Alaskan Arctic and sub-Arctic, as has been suggested by other studies (Crozier et

217   al. 2008; Irvine and Fukuwaka 2011; Sigler et al. 2011).

218   *4.1 Juvenile Chum Salmon marine-entry timing*

219   Marine-entry timing of juvenile Chum Salmon in this study was consistent between the

220   NBS and CS and among sampling years, which corroborates previous evaluations of marine-

221   entry timing for early life stages of this species. Dates of marine entry in the CS ranged from

222   June 16 in summer 2013 to July 16 in summer 2007, while marine-entry timing in the NBS

223   ranged from June 8 in summer 2007 to July 17 in summer 2012. Merritt and Raymond (1983)

224   observed peak outmigration of juvenile Chum Salmon from the Noatak River, a tributary of

225   Kotzebue Sound and the CS, to occur from mid to late June in 1981. In summer 1986, Martin et

226   al. (1987) observed that catch per unit effort (CPUE) of outmigrating juvenile Chum Salmon in

227   the Yukon River delta peaked from mid to late June. Nemeth et al. (2006) observed similar

228   outmigration timing for juvenile Chum Salmon in northern Norton Sound, with peaks in CPUE

229 occurring in mid-June and mid-July in 2003 and 2004. In summer 2014, CPUE for juvenile

230 Chum Salmon outmigrating from the Yukon River delta peaked the final week of May and again

231 the third week of June (K. Howard, ADF&G, unpublished data). These findings are consistent

232 with known Chum Salmon life-history strategies, where downstream movement of fry occurs

233 after ice break-up in spring and continues through the summer months (Salo 1991; Quinn 2005).

234   There are several environmental determinants of marine-entry timing for juvenile Pacific

235 salmon in Arctic and sub-Arctic regions. Outmigration timing is influenced by the synergistic

236 interaction of increasing photoperiod, water temperature, and river discharge during spring

237 months, which corresponds to spring ice retreat and river ice break-up in high latitude rivers

238 (McCormick et al. 1998; Jensen et al. 2012). These environmental changes are cues for initiating

239 outmigration and downstream movement to marine environments for juvenile salmonids

240 (McCormick et al. 1998; Quinn 2005). Chum Salmon are known to migrate quickly downstream

241 after redd emergence at a rate similar to ambient water velocity (Salo 1991; Quinn 2005). As a

242 result, marine entry of juvenile Chum Salmon is coupled with the timing of these environmental

243 cues during spring as day length increases, discharge increases with ice and snow melt, and

244 water warms during summer months. It has been suggested that the timing of smolt outmigration

245 may be an adaptation to environmental conditions at varying latitudes and systems (Holtby et al.

246 1989; Jensen et al. 2012). Consequently, the consistency in marine-entry timing for juvenile

247 Chum Salmon in this study suggests that the timing of marine entry in the NBS and CS systems

248 may be an adaptation to allow for the greatest utilization of abiotic and biotic resources during

249 the short growing season that occurs at high latitudes (Tomaro et al. 2012; Miller et al. 2014).

250   Although marine-entry timing was consistent between regions and among years in this

251 study, the longer distance that juvenile Chum Salmon travel downstream in NBS tributaries (up

252   to 3,000 km to the headwaters of the Yukon River) compared to Kotzebue Sound tributaries (up

253   to 160 km to the headwaters of the Noatak River; Bigler and Burwen 1984) is likely a

254   contributing factor for higher variability in marine-entry timing of Chum Salmon in the NBS

255   than the CS. Previous studies found that Chum Salmon stocks with different life-history types

256   (i.e., summer and fall Chum Salmon in the Yukon River) could contribute to higher variability in

257   marine-entry timing in the NBS (Martin et al. 1987; Murphy et al. 2009). Nemeth et al. (2006)

258   showed that juvenile Chum Salmon entered the marine environment as three distinct groups in

259   northern Norton Sound, which could also be a factor in variability of marine-entry timing of

260   juvenile Chum Salmon in the NBS. The mixed-stock sampling of these Chum Salmon

261   populations in the marine environment (Kondzela et al. 2014) causes potential restrictions in

262   outmigration timing estimation of juvenile Chum Salmon in these regions. Stock-specific

263   comparisons of size and timing of outmigration at the mouth of the Yukon River and in

264   Kotzebue Sound are needed to provide information on the linkage between survival and life-

265   history dynamics of the different stocks collected in this study. More information on life-history

266   type and river of origin is needed to differentiate marine-entry timing of mixed stocks of Chum

267   Salmon in the NBS and CS.

268   Climate change in the Arctic could influence the timing of marine entry for juvenile

269   Chum Salmon through warming water temperatures and changes in ice break-up timing in

270   spawning tributaries. Marine-entry timing dates for juvenile Chum Salmon in this study

271   corresponded with the timing of ice break-up in the spawning tributaries for Chum Salmon

272   (NBS: the Yukon and Kuskokwim rivers, Norton Sound area, and northeastern Russia; CS: the

273   Seward Peninsula, and the Kobuk and Noatak rivers of Kotzebue Sound; Kondzela et al. 2009,

274   2014). Previous research has shown that ice break-up during spring months is the primary

275   determinant of juvenile salmonid outmigration from freshwater to marine environments (Jutila et

276   al. 2005; Jensen et al. 2012). River ice break-up occurred in early May 2007, mid-May 2012, and

277   late May 2013 in tributaries of the NBS, whereas break-up in tributaries of the CS took place

278   during the final week of May for all three sampling years (NWS 2015). More variable river ice

279   break-up dates in NBS tributaries (NWS 2015), are likely to be contributing factors for the more

280   variable marine-entry timing of Chum Salmon in the NBS.

281   Previous studies have shown that in years when the timing of marine entry for juvenile

282   salmon co-occurs with the availability of lipid-rich copepods and other favorable abiotic

283   conditions (i.e. temperature), fish survival is higher (Cross et al. 2008; Tomaro et al. 2012; Miller

284   et al. 2014). Therefore, earlier river ice break-up in spring that is to be expected to result from

285   warming temperatures in the Arctic could lead to earlier outmigration timing of juvenile Chum

286   Salmon into nearshore marine environments. This potential shift towards earlier outmigration

287   timing could lead to a mismatch in the arrival of juvenile fish to the marine environment relative

288   to prey availability (Satterthwaite et al. 2014), which could have negative impacts on growth and

289   survival during the first marine summer. Altered timing of ice retreat in the Bering and/or

290   Chukchi seas could also cause plankton blooms to occur at different times in the spring, which

291   has implications for the assemblage, quality, and quantity of available zooplankton prey

292   available (Hunt et al. 2011). As a result, alterations to temperature, ice break-up, and river

293   discharge that will likely accompany a warming climate will not only affect the timing of key

294   life-history stages, but also likely the productivity of Chum Salmon in Arctic waters (Crozier et

295   al. 2008; Sigler et al. 2011).

296   *4.2 Juvenile Chum Salmon growth rates*

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297   Juvenile Chum Salmon growth rates in this study were consistent between regions and

298   among years, and are in agreement with previous growth rate estimates for juveniles of this

299   species. For the NBS, growth rates in percent weight-per-day were roughly 5%/d. Similarly,

300   Murphy et al. (2009) estimated growth rates of juvenile Chum Salmon collected from the

301   southern and northern Bering seas in summer 2007 to be 5.1%/d. Relatively high growth rates

302   have also been observed for juvenile Chum Salmon in Puget Sound, Washington (5.7 to 8.6%/d;

303   Duffy et al. 2005), nearshore areas of British Columbia (4 to 6%/d, with an upper limit of

304   6.7%/d; Salo 1991), and thermal-marked Chum Salmon in southeast Alaska (3 to 6%/d; J.

305   Murphy, NOAA, unpublished data). These growth rate estimates suggest that differences in

306   environmental conditions throughout Alaska might differentially affect growth rates of juvenile

307   Chum Salmon in different regions.

308   Observed differences in the daily age at which juvenile Chum Salmon attained the same

309   weight between the NBS and the CS (i.e. fish of the same weight differed by 20 or more marine

310   increments between these regions) suggests that there may be differences in the timing of smolt

311   check formation. There appears to be a time lag between check formation on an otolith and when

312   Sr:Ca ratios are observed to increase following marine entry on that same otolith. The lower

313   observed weight at a given daily age for juvenile Chum Salmon in the NBS could be due to

314   differences in environmental conditions between regions and, in turn, how these differences may

315   affect the timing of the smolt check deposition (Campana 1999), specifically differences in

316   estuarine environments. Kotzebue Sound, the major embayment into which several northwestern

317   Alaskan tributaries flow, is a more typical estuary that transitions from brackish water in the

318   nearshore to more saline water at the outlet to the CS (Merritt and Raymond 1983). Conversely,

319   the Yukon River delta is a large, freshwater-dominated estuary near the river mouth and is highly

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320   variable in salinity between the many different locations in the delta where juvenile Chum

321   Salmon inhabit (Martin et al. 1987; Murphy et al. 2009). These conditions make for somewhat

322   harsh rearing environments for juvenile Chum Salmon; Martin et al. (1987) suggested that

323   Yukon River delta habitats serve as staging areas for juveniles before they quickly move

324   offshore, generally at a smaller size than in typical estuarine environments. These contrasting

325   conditions may be a contributing factor for the later smolt check deposition on juvenile NBS

326   Chum Salmon otoliths and their lower weight at a given age than juvenile Chum Salmon in the

327   CS. When estimated smolt checks were removed from daily age estimates and the subsequent

328   growth models, no differences in growth rate estimates were found, suggesting that the observed

329   differences were likely due to variances in the period of smoltification and/or timing of smolt

330   check formation that occurs between regions and not due to error in the estimated location of

331   smolt checks or daily age.

332   Although the range of juvenile Chum Salmon growth rates estimated in this study are

333   comparable to other studies on early marine growth for this species, variable environmental

334   conditions among sampling years, such as temperature, food availability, and photoperiod may

335   have contributed to the observed differences in growth rates. Warmer water temperatures

336   increase fish metabolic rate and, if thermal maxima have not been reached and food availability

337   is sufficient, fish will grow at faster rates (Brett 1979). During this study, mean SST was 1°C

338   warmer during summers 2007 and 2013 than in summer 2012 in both regions (L. Eisner, NOAA,

339   unpublished data). The relatively high percent weight-per-day growth rate of juvenile Chum

340   Salmon in the CS in 2013 suggests that conditions were more energetically favorable for growth

341   and that prey quality may be higher in the CS than the NBS, perhaps due to the shallower shelf

342   habitat (i.e. warmer SSTs; Grebmeier et al. 2006), coupled with increased feeding opportunities

15

343 and greater primary and secondary productivity from longer day lengths/photoperiod (Moss et al.

344 2009a). Although SSTs were relatively warm in summers 2007 and 2013 for both regions, the

345 relatively low growth rate exhibited by juvenile Chum Salmon in the CS in summer 2007

346 (4.2%/d) is most likely a result of sampling dates that occurred one month later than in

347 2012/2013. Because growth rates typically decline as fish grow larger and older (Brett 1979), the

348 later sampling dates in the CS in 2007 may have contributed to the lower observed weight-at-age

349 growth for that region/year combination.

350   The quality and quantity of prey resources available for juvenile Chum Salmon, as well

351 as the amount of lipid stores that can be derived from those food sources, is important for growth

352 during the early marine period. The significantly higher weight-at-age growth relationship in the

353 CS in summer 2013 and lack of differences in length-at-age relationships between all region/year

354 combinations suggests that length may not be as important as weight when it comes to energy

355 storage to survive the winter. These results are consistent with the findings of Andrews et al.

356 (2009) in which an uncoupling between length and total energy content was observed for eastern

357 Bering Sea juvenile Pink Salmon *Oncorhynchus gorbuscha*. Although body weight is not

358 necessarily indicative of accumulated caloric content or stored energy reserves, juvenile salmon

359 have been shown to exhibit higher total energy content and lipid stores at cooler thermal regimes,

360 which is consistent with the thermal regime in the Bering and Chukchi seas since 2006 (Andrews

361 et al. 2009; Moss et al. 2009b). This current thermal regime supports energetically dense prey

362 that are beneficial for juvenile salmon growth, which may provide one explanation for the

363 consistently high growth rates observed in both regions of this study (Farley et al. 2009; Hunt et

364 al. 2011). The higher growth rate observed in the CS in summer 2013 suggest that conditions

365 were more energetically favorable for growth and that prey quality may be higher in the CS than

366 the NBS, perhaps due to the shallower shelf habitat, high primary productivity, and longer day

367 lengths/photoperiod (Grebmeier et al. 2006; Moss et al. 2009a; Zador 2013).

368   Growth rates for juvenile salmon in the NBS and CS may respond to climate change due

369 to altered metabolic rates and timing of important life-history periods relative to changes in prey

370 abundance, composition, and distribution (Crozier et al. 2008; Nielsen et al. 2013). Higher

371 growth rates of juvenile Chum Salmon in the NBS and CS would be expected to yield higher

372 survival through the first winter period, with positive implications for adult fish returns (Moss et

373 al. 2005). Although warmer SSTs might benefit growth when prey quality is high, bottom-up

374 regulation of nutrients and prey availability will likely be affected by changes in sea ice extent,

375 the timing of sea ice retreat and, therefore, plankton production and growth (Hunt et al. 2011).

376 Continued monitoring of Chum Salmon in the NBS and CS will lead to a greater understanding

377 of how climate change will affect early marine growth and subsequent survival to the adult life

378 stage. The complexities of juvenile salmon growth cannot be understated and, while this study

379 provides insight into differences between regions, the causal mechanisms influencing growth

380 rates of juvenile Chum Salmon in the NBS and CS must be further investigated.

381 **5. Conclusions**

382   The results of this study suggest that juvenile Chum Salmon in the NBS and CS currently

383 exhibit consistent early marine life-history characteristics in the NBS and CS, such as marine-

384 entry timing and growth rates during their first marine summer, despite some differences in

385 environmental conditions between regions and among years. However, changes in climate

386 variability in the Arctic have the potential to alter key life-history stages of Pacific salmon stocks

387 in Alaska, including entry to the marine environment and early marine growth. Warming oceans

388 with higher SSTs during summer months have been shown to support higher marine survival

389   rates and productivity for some Pacific salmon populations in the northeast Pacific, Gulf of

390   Alaska, and the Bering Sea (Mueter et al. 2002; Mantua 2009). While the relatively warmer

391   SSTs might have positively influenced juvenile Chum Salmon growth in this study, the effects

392   that warming temperatures may have on other factors such as marine-entry timing, prey

393   availability, and survival during their first marine year are also important to understand within

394   the context of climate change. Warming temperatures in freshwater environments might have

395   significant effects on the outmigration timing of salmon smolts, leading to potential mismatches

396   with optimal prey availability in nearshore marine environments (Tomaro et al. 2012;

397   Satterthwaite et al. 2014). This complex suite of biotic and abiotic variables that influence

398   juvenile Chum Salmon early life history in the NBS and CS and the complexity associated with

399   early growth dynamics of this species cannot be understated. As a result, it is critical to

400   understand how these environmental conditions interact to impact early life stages and

401   subsequent adult returns of Chum Salmon due to climate change in these regions.

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413   Fisheries Service, NOAA.

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586 **Table 1.** Number of juvenile Chum Salmon otoliths used for aging and chemical analysis by

587 region and year. Numbers with asterisks (*) denote samples prepared, read, and analyzed by J.

588 Murphy, NOAA, Juneau, Alaska. Note: NBS 2013 samples are not included due to a flooding

589 event that occurred onboard in which all samples were either lost at sea or recovered and

590 rendered unusable.

Region	Year	Stations	Total fish subsampled from all stations	Otoliths read	Otoliths used for chemical analysis
Chukchi Sea	2007	20	292	108	22
	2012	3	104	98	20
	2013	3	95	93	20
	Total	26	491	299	62
Northern Bering	2007	36	559	112*	112*
Sea	2012	16	480	109	20
	Total	52	1039	221	132

591

592 **Table 2.** Aging analysis of marine otolith increments for juvenile Chum Salmon listed by region, year, and fork length bin. Dashes (-)

593 indicate that no fish were collected in that length bin. Both calendar and Julian dates (in parentheses) are provided. Numbers with

594 asterisks (*) denote samples prepared, read, and analyzed by J. Murphy, NOAA, Juneau, Alaska.

Region	Year	Fork length bin (mm)	Weight range (g)	Number of otoliths	Mean marine increments	StDev marine increments	Mean capture date (Julian)	Mean entry date (Julian)	Minimum entry date (Julian)	Maximum entry date (Julian)
Chukchi	2007	120-140	20-30	3	57.67	1.53	9/8 (251)	7/12 (193)	7/11 (192)	7/16 (197)
Sea		141-160	-	-	-	-	-	-	-	-
		161-180	44	1	64.00	0.00	9/11 (254)	7/9 (190)	7/9 (190)	7/9 (190)
		181-200	64-86	45	73.16	3.57	9/9 (252)	6/28 (179)	6/22 (173)	7/7 (188)
		201-220	76-126	59	76.86	3.00	9/9 (252)	6/24 (175)	6/16 167)	7/1 (182)
		Mean			74.67			6/26 (177)		
	2012	80-100	7-12	3	37.00	2.65	8/12 (225)	7/6 (188)	7/3 (185)	7/10 (192)
		101-120	10-20	18	39.17	2.36	8/11 (224)	7/3 (185)	6/28 (180)	7/8 (190)
		121-140	14-34	54	43.26	2.93	8/11 (224)	6/29 (181)	6/22 (174)	7/7 (189)
		141-160	22-40	23	49.35	3.19	8/11 (224)	6/23 (175)	6/14 (166)	6/28 (180)
		Mean			43.75			6/29 (181)		

	2013	80-100	6	3	32.67	1.53	8/8 (220)	7/6 (187)	7/5 (186)	7/8 (189)
		101-120	8-16	25	37.32	2.48	8/8 (220)	7/1 (182)	6/27 (178)	7/7 (188)
		121-140	18-30	40	41.95	3.00	8/9 (221)	6/28 (179)	6/24 (175)	7/6 (187)
		141-160	22-38	25	47.92	3.48	8/10 (222)	6/23 (174)	6/16 (167)	7/2 (183)
		Mean			42.01			6/28 (179)		
Northern Bering	2007	140-160	30-44	23	76.61	4.52	9/18 (261)	7/4 (185)	6/24 (175)	7/12 (193)
Sea		161-180	36-65	21	80.67	5.49	9/23 (266)	7/2 (183)	6/22 (173)	7/12 (193)
		181-200	58-86	23	86.22	5.13	9/24 (267)	6/30 (181)	6/20 (171)	7/14 (195)
		201-220	82-114	20	89.40	4.88	9/23 (266)	6/26 (177)	6/12 (163)	7/11 (192)
		221-240	110-154	22	95.27	6.27	9/24 (267)	6/21 (172)	6/10 (161)	7/1 (182)
		241-260	147-187	3	99.75	3.79	9/29 (272)	6/18 (169)	6/14 (165)	7/1 (182)
		Mean			85.88			6/28 (179)		
	2012	120-140	16-26	9	68.33	3.04	9/16 (260)	7/9 (191)	6/30 (182)	7/17 (199)
		141-160	19-43	31	76.74	4.57	9/17 (261)	7/2 (184)	6/27 (179)	7/8 (190)
		161-180	38-62	46	83.22	3.87	9/22 (266)	6/30 (182)	6/25 (177)	7/7 (189)
		181-200	50-79	17	86.94	3.52	9/23 (267)	6/28 (180)	6/23 (175)	7/4 (186)

201-220	86-104	6	89.38	4.18	9/24 (268)	6/26 (178)	6/21 (173)	7/4 (186)
Mean			81.08			7/1 (183)		

595

596   **Figure 1.** Station array and catches of juvenile Chum Salmon during the 2012 (left) and 2013 (right) Arctic Eis surveys. Circle sizes

597   represent catches for one 30-minute surface trawl at each station. Stations with an "X" denote locations where no juvenile Chum

598   Salmon were caught. Reproduced with permission from NOAA.

599   **Figure 2.** Linear regression models of fork length-at-age for (a) Chukchi Sea and (b) northern

600   Bering Sea juvenile Chum Salmon. The slope coefficient in each equation indicates the growth

601   rate of that particular region and year.

602 **Figure 3.** Exponential growth models of wet weight-at-age for (a) Chukchi Sea and (b) northern

603 Bering Sea juvenile Chum Salmon. The exponential term in each equation indicates the growth

604 rate of that particular region and year when multiplied by 100.

(a)
- ● 2007 y = 2.3068x + 26.957
- ○ 2012 y = 2.4683x + 22.423
- ● 2013 y = 2.5997x + 20.387

(b)
- ▲ 2007 y = 2.8177x - 50.951
- △ 2012 y = 2.4098x - 28.368

Marine age (d)

(a)
- ● 2007 $y = 3.6162e^{0.0418x}$
- ○ 2012 $y = 2.0776e^{0.0534x}$
- ◉ 2013 $y = 1.1426e^{0.0677x}$

(b)
- ▲ 2007 $y = 0.9853e^{0.0496x}$
- △ 2012 $y = 0.8373e^{0.0488x}$

Marine age (d)