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Growth and condition of juvenile chum and pink salmon in the northeastern Bering Sea

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ABSTRACT

As the Arctic continues to warm, abundances of juvenile Pacific salmon (*Oncorhynchus* spp.) in the northern Bering Sea are expected to increase. However, information regarding the growth and condition of juvenile salmon in these waters is limited. The first objective of this study was to describe relationships between size, growth, and condition of juvenile chum (*O. keta*) and pink (*O. gorbuscha*) salmon and environmental conditions using data collected in the northeastern Bering Sea (NEBS) from 2003–2007 and 2009–2012. Salmon collected at stations with greater bottom depths and cooler sea-surface temperature (SST) were longer, reflecting their movement further offshore out of the warmer Alaska Coastal Water mass, as the season progressed. Energy density, after accounting for fish length, followed similar relationships with SST and bottom depth while greater condition (weight-length residuals) was associated with warm SST and shallower stations. We used insulin-like growth factor-1 (IGF-1) concentrations as an indicator of relative growth rate for fishes sampled in 2009–2012 and that found fish exhibited higher IGF-1 concentrations in 2010–2012 than in 2009, although these differences were not clearly attributable to environmental conditions. Our second objective was to compare size and condition of juvenile chum and pink salmon in the NEBS between warm and cool spring thermal regimes of the southeastern Bering Sea (SEBS). This comparison was based on a hypothesis informed by the strong role of sea-ice retreat in the spring for production dynamics in the SEBS and prevailing northward currents, suggesting that feeding conditions in the NEBS may be influenced by production in the SEBS. We found greater length (both species) and condition (pink salmon) in years with warm thermal regimes; however, both of these responses changed more rapidly with day of year in years with cool springs. Finally, we compared indicators of energy allocation between even and odd brood-year stocks of juvenile pink salmon, finding support for the idea that the even-year stock allocates more energy to storage, as opposed to growth, than does the odd-year stock. Over all, our results support the idea that sea-ice dynamics influence energy allocation and growth of juvenile salmon in the northern Bering Sea and provide a foundation for further understanding of how environmental conditions influence juvenile salmon at the northern edge of their range.

1. Introduction

Chum (*Oncorhynchus keta*) and pink (*O. gorbuscha*) salmon provide vital ecological, economic, and subsistence resources to the peoples of western Alaska. Chum and pink salmon are broadly distributed across the Pacific Ocean and inhabit the most northern range of Pacific salmon, with a few populations natal to Alaska's North Slope rivers (Irvine et al., 2009). The cold-water tolerance of these species and their minimal use of freshwater habitat have enabled populations to colonize sub-Arctic and Arctic regions (Craig and Haldorson, 1986; Irvine et al., 2009). These characteristics make chum and pink salmon likely candidates for future northern range expansion as Arctic climate continues to warm (Nielsen et al., 2012). In recent years, populations of chum and pink salmon in the North Pacific Ocean have increased, due primarily to increased hatchery production but also enhanced marine survival (Ruggerone et al., 2010). Furthermore, significant abundances of juvenile chum and pink salmon have been observed in the northeastern Bering Sea (NEBS) and southern Chukchi Sea (Moss et al., 2009). These observations parallel reported increases

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in the abundance of salmon by subsistence users in Arctic and sub-Arctic habitats in northwestern Alaska (Eggers et al., 2011; Carothers et al., 2013) and highlight the need for research on juvenile salmon at higher latitudes. In northern habitats, growth and condition are likely key factors that provide insight into marine survival.

Changing ocean conditions may affect marine survival of juvenile salmon, through effects on growth and nutritional condition. Marine survival of salmon may be dependent on growth accrued over the first summer in the ocean (Beamish and Mahnken, 2001; Farley et al., 2007). Marine survival during their first winter may also be dependent on juvenile salmon reaching threshold levels of nutritional condition (from hereafter referred to as 'condition') (Beamish and Mahnken, 2001). There is a strong correlation between salmon growth and temperature, given that nutritional needs are met and temperatures are within the thermal limits of the organism (Larsen et al., 2001; Beckman et al., 2004a,b; Andrews et al., 2009). However, temperature has been shown to have contrasting effects on growth and condition of juvenile salmon (Andrews et al., 2009; Davis et al., 2009; Heintz, 2009). For example, Andrews et al. (2009) found that juvenile pink salmon in the NEBS were longer during warm years, but less energy dense. Conversely, juvenile pink salmon sampled during cool years were shorter, but more energy dense (Andrews et al., 2009). While it is likely that the relationship between temperature and condition is due to a combination of physiological and environmental variables, lab studies have shown that cooler temperatures facilitate lipid storage in juvenile salmon (Heintz, 2009). To further investigate relationships between physiological and environmental variables, this study describes relationships between juvenile chum and pink salmon growth, condition, and environmental variables measured within the NEBS.

While sea ice extent and timing of sea ice retreat has remained relatively consistent in the NEBS, sea ice conditions in the southeastern Bering Sea (SEBS) have alternated between periods of early and late sea ice retreat (Hunt et al., 2011). Anomalously warm May spring sea surface temperatures and early sea ice retreat occurred in 2002–2005. From 2006–2013, the region was characterized by anomalously cool May spring sea surface temperatures and late sea ice retreat (Andrews et al., 2009; Farley and Trudel, 2009; Overland et al., 2012). Warm years were found to support open-water spring blooms that led to a 70% increase in primary production (Brown and Arrigo, 2013). However, in the SEBS, these open water blooms supported warm-water species of zooplankton that were lipid-poor, reducing the amount of energy available to higher trophic levels. Conversely, ice-associated blooms that occurred during years of late ice-retreat supported lipid-rich, cold-water species of zooplankton, increasing the amount of energy available to higher trophic levels (Coyle and Pinchuk, 2002; Coyle et al., 2011; Hunt et al., 2011). Thus, it has been interpreted that ice-associated blooms provide an energy-rich prey source for pelagic fishes, such as juvenile walleye pollock and salmon. As prevailing currents advect waters from the SEBS northward into the NEBS (Johnson et al., 2004), we hypothesized that fundamental differences in production between early and late ice retreat in the SEBS would have downstream consequences for fish consumers in the NEBS, such as salmon and their prey.

Environmental variables may influence growth and condition of juvenile salmon, but there may also be an important genetic influence on juvenile pink salmon. Pink salmon have a unique two-year life cycle, with even and odd stocks (with 'even' or 'odd' referring to the year of spawning) being genetically distinct (Aspinwall, 1974; Beacham and Murray, 1988; Beacham et al., 2012). Genetic divergence between even and odd stocks may include differences in metabolic strategy (Beamish, 2012). The short life cycle of pink salmon has corresponded with the evolution of rapid marine growth (Ricker, 1976; Brett, 1979). In recent years, odd stocks of pink salmon in the Fraser River system, British Columbia, have increased, while even stocks have remained fairly constant (Beamish, 2012). Beamish (2012) attributed this to evolved differences in metabolic strategy during the first marine summer between stocks, with odd stocks allocating more energy to growing in length and even stocks allocating more energy to fat storage. This difference in energy allocation would allow odd stocks to benefit from the increased prey production during late fall that has been attributed to warming off the coast of British Columbia, and thus could explain why odd stocks have increased in abundance in that region while even stocks have not (Beamish, 2012).

We used data from integrated ecosystem surveys conducted during late summer in the northeastern Bering Sea from 2003 to 2013 (see Farley et al., 2009) to examine how spring thermal regime and summer ocean conditions influence size, growth, and condition of juvenile chum and pink salmon in the NEBS. Specifically, our objectives were to 1) describe how body length, condition, and growth were related to environmental variables measured at time of capture, 2) determine whether length and condition in the NEBS differed between warm and cool spring thermal regimes of the SEBS, and 3) to test the odd/even year energy allocation strategy (growth vs. storage) hypothesis (Beamish, 2012) for pink salmon. For objectives 1 and 2, we hypothesized that juvenile pink and chum salmon would be smaller but in better condition during the cool spring thermal regime based on expected trophic consequences of ice-associated bloom in the SEBS. For objective 3, based on Beamish's (2012) hypothesis, we predicted that odd stocks should be longer, while even stocks should show higher energy density and mass for their length, after accounting for secular variation in environmental conditions. Our results provide a foundation for understanding how climate-induced changes in ecosystem structure may affect condition and growth of juvenile pink and chum salmon in the NEBS.

2. Material and methods

2.1. Field sampling

Surveys were conducted each September from 2003 to 2013 (except in 2008 due to insufficient funding) in the northeastern Bering Sea. Over the time frame of our analysis, the mean geographic position of the entire NEBS survey tended to shift northward and eastward (further inshore), and also tended to occur earlier. For these reasons, we only included stations sampled between 59.92 °N to 64.06 °N and −174.00 °W to −165.95 °W in our analyses (Fig. 1). Additionally, the direction of sampling varied among years, with sampling occurring from south to north in 2003, 2007, 2009–2011 and from north to south in 2004–2006 and 2012–2013.

Juvenile salmon were collected following methods described in Murphy et al. (2003) and Farley et al. (2009). All sampling was done during daylight hours, from approximately 0700 AKDT to 2300 AKDT. Oceanographic data were collected at each trawl station immediately prior to deploying the trawl. Vertical profiles of temperature, salinity, chlorophyll-a fluorescence, light transmission, and photosynthetically active radiation (PAR) were measured with a Sea-Bird Electronics Inc. SBE 25 (2003–2005) and SBE 911/17 (2005-current) Sealogger Conductivity-Temperature-Depth profiler (CTD).

2.2. Biological measurements

We characterized juvenile salmon growth and condition in the NEBS using body length, weight-length residuals, insulin-like growth factor-1 (IGF-1), and energy density. Weight-length residuals provide a simple method for assessing body mass while controlling for variation in body length (Jakob et al., 1996). The