Is a Warming Bering Sea Leading to Smaller Chinook Salmon?

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The past 50 years have seen declines in size and age of adult Chinook salmon (*Oncorhynchus tshawytscha*) along its entire eastern Pacific range, including Alaska. Ohlberger et al. (2018) summarized five hypotheses for the observed declines, including four previously proposed hypotheses: 1) size-selective harvest; 2) influence of hatchery production; 3) competition among Pacific salmon populations in the ocean; and 4) climate/environmental variation. The authors additionally proposed a new hypothesis: 5) increased predation upon older Chinook salmon. While none of these hypotheses are mutually exclusive, Ohlberger et al. (2018) concluded that hypotheses 1–4 were insufficient to explain the range-wide declines. Here, we suggest that hypothesis 4, climate variation, plays an important role for earlier maturation of Chinook salmon, at least towards the northern part of its range. We summarize two previously published studies (Siegel et al. 2017, 2018) demonstrating that environmental forcing, as expressed by sea surface temperature (SST), is associated with earlier maturation and thus smaller adult size of Chinook salmon.

Fig. 1. Map of study area, showing location of East Fork of the Andreafsky River and the Kogrukluk River; inset shows their location in western Alaska and the region of the central Bering Sea for which average April–December SSTs were calculated (a) and image of Chinook salmon scale showing annual growth zones where FW = freshwater growth and SW = saltwater growth (b). Adapted from McPhee et al. (2016) and Siegel et al. (2018).

The studies of Siegel et al. (2017, 2018) were based on retrospective analyses of adult salmon scales collected over several decades at weirs on two rivers in western Alaska (Fig. 1a): the Kogrukluk River (Kuskokwim River drainage; brood years 1977–2006) and the East Fork of the Andreafsky River (Yukon River drainage; brood years 1990–2005). Adult scales (25 per sex and age class) were digitized and measured as described in McPhee et al. (2016), and annual growth zones (Fig. 1b) were quantified and used to infer annual growth in length. Run reconstructions that accounted for harvest were used to estimate the age composition of recruits on a per-brood-year basis and to derive age-weighted mean annual growth (as described in Siegel 2017). Environmental variability was represented by annual SST from the central Bering Sea (60.0°–54.3°N, 178.1°E–170.6°W) averaged over April–December (Fig. 1a; see Siegel et al. 2017 for details).

Fig. 2. Average annual growth versus annual average April–December SST for Andreafsky River SW1 (a) and SW2 (b) and Kogrukluk River SW1 (c) and SW2 (d). Adapted from Siegel et al. (2017).
Using probabilistic maturation reaction norms that accounted for growth history (i.e., using each annual growth increment rather than total length at maturation), we found that faster early marine growth was associated with earlier age at maturity (Siegel et al. 2018; see also McPhee et al. 2016). By examining correlations between SST, annual average growth, and average recruit age, we found that early marine growth was faster in years with warmer SST (Fig. 2), and that warmer years were associated with younger average age of recruits (Fig. 3). Additionally, by fitting maturation models to average growth over the time series to calculate a ‘probability of maturation for average growth’ (PMAG), we found that males were more likely to mature at the youngest age (age 3) in warmer years, even after accounting for the effects of growth (Fig. 4). Taken together, these results provide support for the idea that environmental variation plays an important role in determining the size of Chinook salmon.

**Fig. 3.** Average age of Andreafsky River recruits versus SST during the first year of marine growth (a) and average age of Kogrukuk River recruits versus SST during the second year of marine growth (b).

**Fig. 4.** Probability of maturation with average growth (PMAG) for the earliest male maturation decision (age 4) for Andreafsky River Chinook salmon versus SST during the first year of marine growth (a) and for Kogrukuk River Chinook salmon versus SST during the second year of marine growth (b). Adapted from Siegel et al. (2017).

**Fig. 5.** Probability of maturation with average growth (PMAG) against time for the two major maturation decisions (age 4 and 5 for males, M; age 5 and 6 for females, F) for the Andreafsky River (a) and the Kogrukuk River (b). Adapted from Siegel et al. (2018).
The central and eastern Bering Sea has not warmed steadily over the three decades covered by our study, suggesting that other mechanisms are also influencing age at maturity in these populations [although we note that the western Bering Sea shows a more pronounced warming trend (McPhee unpublished data), and these stocks are thought to spend a significant amount of their life cycle rearing there (Bugaev and Myers 2009)]. However, we found that temporal trends in PMAG were uniformly positive (Fig. 5), indicating a shift in the size threshold at which these salmon mature and suggesting that additional forces are causing Chinook salmon to mature earlier. One explanation could be fisheries selection reducing the number of older fish making it to the spawning grounds. Alternatively, increased natural mortality of the oldest fish (hypothesis 5 of Ohlberger et al. 2018) might contribute to these patterns, if the slowest growing of the older fish were most susceptible to predation. At this time, insufficient data exist to test these hypotheses, but future simulation studies could help identify the range of mortality values that could give rise to the observed patterns.

REFERENCES


