Linking Abundance, Distribution, and Size of Juvenile Yukon River Chinook Salmon to Survival in the Northern Bering Sea

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Significant harvest restrictions, including the closure of commercial fisheries and reductions in subsistence fisheries, have been implemented in response to declining production levels of Yukon River Chinook salmon stocks. Causes of their production decline are unclear; however concurrent declines throughout the Yukon River drainage (JTC 2013), production declines in other regions of Alaska (ADFG 2012), declines in marine survival in southeast Alaska Chinook salmon stocks (Guyon et al. 2013), and the presence of bycatch in marine fisheries (Stram and Ianelli 2009) emphasize the importance of ocean conditions and the marine life-history stage of Chinook salmon.

Yukon River Chinook salmon utilize marine habitats adjacent to or on the eastern Bering Sea shelf throughout most of their marine life-history stage (Myers, et al. 2009). Sea ice and its impact on ecosystem level processes on the shelf is an important feature in the marine ecology of western Alaska salmon populations (Farley and Trudel 2009; Moss et al. 2009). Although the principal change in Arctic sea ice has occurred during the summer melt season through the loss of multi-year ice levels, sea ice primarily impacts the Bering Sea through winter/spring ice extent and seasonal ice levels. Winter/spring ice extent has not declined in a manner similar to summer ice and has actually increased in recent years, resulting in recent cooling of the Bering Sea (Stabeno et al. 2012). We review information on juvenile abundance, distribution, and size in relation to survival of Yukon River Chinook salmon and describe how they are connected to sea ice and broad-scale temperature changes in the eastern Bering Sea.

A Canadian-origin juvenile abundance index constructed from surface trawl catch, stock composition, and mixed layer depth data was used to describe juvenile abundance. Juvenile data were provided by the Alaska Fisheries Science Center as part of the US Bering-Aleutian Salmon International Survey (NPAFC 2001) and similar ecosystem-based projects in the northern Bering Sea. Surface trawl operations are described in Murphy et al. (2003) and Farley et al. (2009).

Average juvenile Chinook salmon CPUE (catch/km^2) was expanded to an abundance index by the survey area, sampling grid area, and number of stations. The northern Bering Sea was divided into four spatial strata: 60°-62°N, 62°-64°N, Norton Sound, and Bering Strait, and corrections were used to adjust for inconsistent survey effort in the Norton Sound and Bering Strait strata over time. A single nucleotide polymorphism (SNP) genetic baseline (Templin et al. 2011b) was used to estimate stock mixtures of juvenile Chinook salmon through genetic mixed stock analysis (Pella and Masuda 2001). Canadian-origin stock proportions in the northern Bering Sea were reported in Murphy et al. (2009), Templin et al. (2011a), and Guthrie et al. (2013).

Mixed layer depth (MLD) corrections were applied to juvenile catch data to adjust for variation in trawl depth and vertical distribution of juvenile Chinook salmon by assuming a uniform distribution of juvenile Chinook salmon within the surface mixed layer. The MLD was defined as the depth where seawater density increased by 0.10 kg/m^3 relative to the surface (Danielson et al. 2011). The MLD correction to trawl catch, θy, was estimated as:

$$\theta_y = \sum_j \frac{MLD_{j,y}}{TD_{j,y}} C_{j,y},$$

where $MLD_{i,y}$, $TD_{j,y}$, and $C_{j,y}$ are the mixed layer depth, trawl depth, and catch, respectively, at stations, *j*, where trawl depth is above the mixed layer, and year, *y*. MLD trawl catchability correction, q_y, was estimated by:

$$q_y = \frac{\theta_y}{\sum_i C_{i,y}},$$

where $C_{i,y}$, is the catch at the i^{th} station in year, *y*.

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Brood year returns of Canadian-origin Chinook salmon to the Yukon River (JTC 2013) and the Canadian-origin juvenile index were used to define the relationship between juvenile and adult abundance. Brood year returns were rescaled to juvenile year based on the assumption that all juveniles were freshwater age-1. Although freshwater age-0 and age-2 Chinook salmon are present in the juvenile population, their numbers are low relative to the number of freshwater age-1 juveniles.

Juvenile scales and body size in the northern Bering Sea (2002-2007), and age structure and scales of adult Chinook salmon returning to the Yukon River (2004-2011) were used to model size-selective mortality. A subsample of 150 scales from Pilot Station in the lower Yukon River was digitized for each juvenile year proportional to age structure. The average (22) and standard deviation (1.98) of juvenile scale circuli counts after the last freshwater annulus were used as the sampling distribution of adult scale circuli. Adult scale measurements were converted to juvenile length (mm) from the juvenile scale radius (mm) model (length = 149.98*radius+49.367) and reconstructed juvenile lengths (mm) were converted to weight (g) with the length-weight relationship for juvenile Chinook (ln(weight) = 3.0816*ln(weight)-11.735). Weight models were used to describe size-selective mortality as size-selective mortality at this life-history stage is believed to be primarily a function of energy storage (Beamish and Mahnken 2001). Due to the underlying energy allocation patterns of juvenile Chinook salmon in the northern Bering Sea, energy density is primarily a function of size and is linear with juvenile weight (Fig. 1). Size selective mortality probabilities, ρ_i, were estimated from the proportion of juvenile, j_i, and surviving adults, a_i, within each weight interval, i, as:

$$\rho_i = \frac{\frac{j_i}{a_i}}{\left(\frac{j_i}{a_i} + 1\right)}.$$

Generalized additive models (Chambers and Hastie 1992) were fit to mortality probabilities and used to describe size-selective mortality in juvenile Chinook salmon.

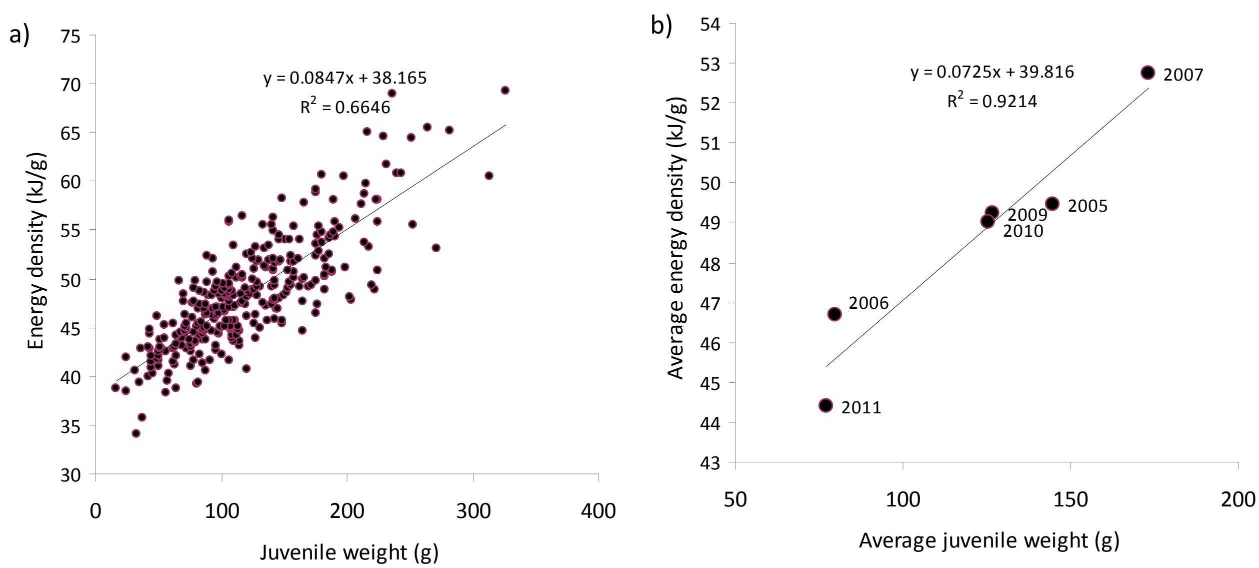

Fig. 1. The relationship between weight (g) and energy density (kJ per gram) of juvenile Chinook salmon in the northern Bering Sea for individual fish (a) and by year (b).

Average seawater temperature within the mixed layer from the BASIS surface trawl surveys were used to define inter-annual variability in seawater temperature of the northern Bering Sea shelf. Significant differences in juvenile abundance, distribution, and size between warm (2003-2007) and cold (2009-2011) years were evaluated with a Student's t-test.

Juvenile abundance of the Canadian-origin stock group was positively correlated with adult returns (r = 0.89, p = 0.04 r^2 = 0.62 n = 5; Fig. 2) indicating that juvenile abundance explains a significant (p < 0.05) amount of the variability present in recent adult returns. This emphasizes the importance of freshwater and estuarine (early marine) life history stages to inter-annual variability in adult returns. However, the average juvenile survival index is low (0.06; Table 1) and, therefore, mortality after the juvenile stage is important to their overall production; ecosystem and fishery effects on survival after the juvenile stage are needed to adequately address production dynamics of Yukon River Chinook salmon.

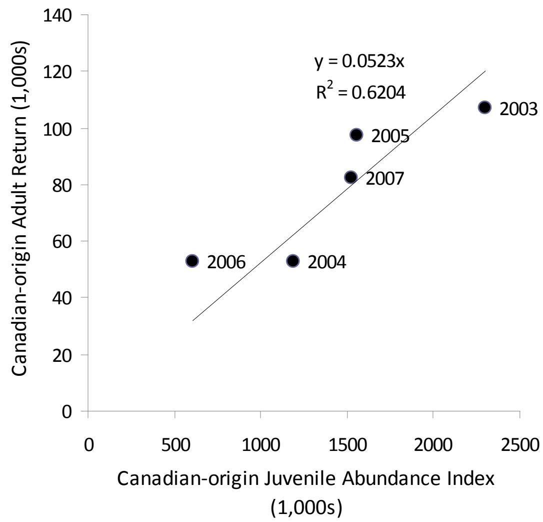

Fig. 2. The relationship between the Canadian-origin juvenile Chinook salmon abundance index and adult returns by juvenile year (2003-2007). Juvenile year is added to each data point.

Temperature limitations in the northern Bering introduce important constraints on juvenile migration. Juveniles are unlikely to survive in the northern Bering Sea once sea ice forms, and quite possibly prior to the formation of sea ice. Sea ice begins to form in coastal habitats utilized by juvenile Chinook in early November and the entire northern shelf is ice covered by early January. Sea water freezes at approximately -1.7 °C in the northern Bering Sea as its salinity is in the range of 30-31 PSU (practical salinity unit). Due to shallow water depths in the northern Bering Sea, the entire water column drops below zero as sea ice forms (under ice temperatures reported in Danielson et al. 2006). Salmon lose metabolic function and cannot survive in temperatures near zero for any length of time (Brett and Alderdice 1958). The southern Bering Sea is believed to be the closest suitable overwinter habitat for Yukon River Chinook salmon. Northward dispersal/migration of juveniles through increased current speeds or northward migration behavior will displace juveniles away from winter habitats and may impact their survival (Fig. 3). Average latitude position of juveniles was negatively correlated with survival ($r = -0.68$, $n = 5$, $p = 0.21$; Table 1), and provides support (but not significant ($p < 0.05$) support) for the linkage between juvenile migration and survival.

Table 1. Juvenile abundance index, mixed layer depth (MLD) corrections, Canadian-origin stock proportions in northern Bering Sea juveniles, adult returns, and survival index for Canadian-origin Yukon River Chinook salmon from surface trawl surveys in the northern Bering Sea (2003-2011). Average length, weight, and latitude position of juvenile Chinook in the northern Bering Sea, and average seawater temperatures above the mixed layer depth from surface trawl surveys in the Bering Sea. T-test probabilities of significant differences in abundance, length, weight, latitude, and temperature between warm (2003-2007) and cold (2009-2011) years.

Juvenile Year	Juvenile Index (1,000s)	MLD correction	Canadian Stock Proportion	Canadian Juvenile Index (1,000s)	Canadian Return (1,000s)	Survival Index	Length (mm)	Weight (g)	Latitude (°)	MLD Temp. (°C)
2003	4,728	0.14	0.43	2,302	107	0.05	201	102	63.18	10.15
2004	2,064	0.12	0.52	1,189	53	0.04	218	130	62.93	10.88
2005	2,563	0.29	0.47	1,556	97	0.06	217	125	62.33	9.37
2006	1,179	0.13	0.46	608	53	0.09	194	87	62.52	9.16
2007	2,748	0.16	0.48	1,523	82	0.05	231	155	63.17	8.96
2008										
2009	1,846	0.01	0.45	842			223	136	61.95	8.03
2010	1,558	0.05	0.43	702			206	108	61.96	8.34
2011	3,209	0.16	0.46	1,701			195	89	62.02	7.90
2003-2007	2,656	0.17	0.47	1,436			212	120	62.83	9.70
2009-2011	2,204	0.07	0.45	1,082			208	111	61.98	8.09
p(T <= t, alpha =.05)				0.43			0.66	0.56	**<0.01**	**<0.01**

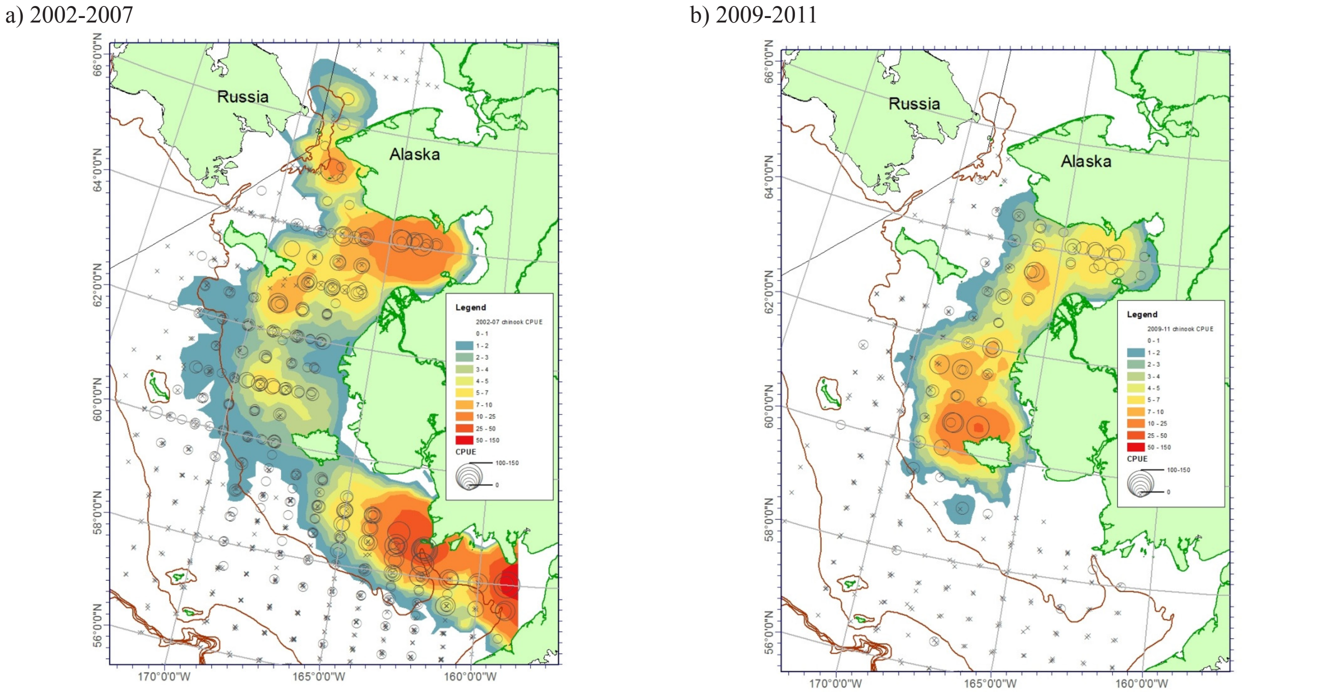

Fig. 3. Distribution of juvenile Chinook salmon catch-per-unit-effort (CPUE, catch/km^2) from surface trawl surveys on the eastern Bering Sea Shelf, August-September (2002-2011). Circles are CPUE data at each sample location and average CPUE is shaded from low to high with hues from blue to red. Distributions are shown for two time periods (a) 2002-2007 and (b) 2009-2011. Bering Sea temperatures were warmer during 2002-2007 than 2009-2011.

Size-selective mortality is evident in size distribution differences between juveniles and survivor reconstruction from adult scales (Fig. 4). Juveniles had a lower average weight (141 g) and minimum weight (18 g) than survivors (average weight of 169 g and minimum weight of 62 g). The mortality model for Yukon River Chinook salmon indicates that mortality is very high for the smallest juveniles (these are primarily late out-migrating freshwater age-0 Chinook salmon, distinguishable from age-1 Chinook by the presence of freshwater parr marks), but rapidly declines to the point of neutral selection (mortality probability of 0.5) at approximately 138 g (Fig. 5). Size-selective mortality is believed to introduce important constraints on juvenile life-history through selection against late out-migration of freshwater age-0 juveniles in Yukon River Chinook salmon. Due to the presence of size-selective mortality, faster growth rates and larger juvenile sizes will improve survival.

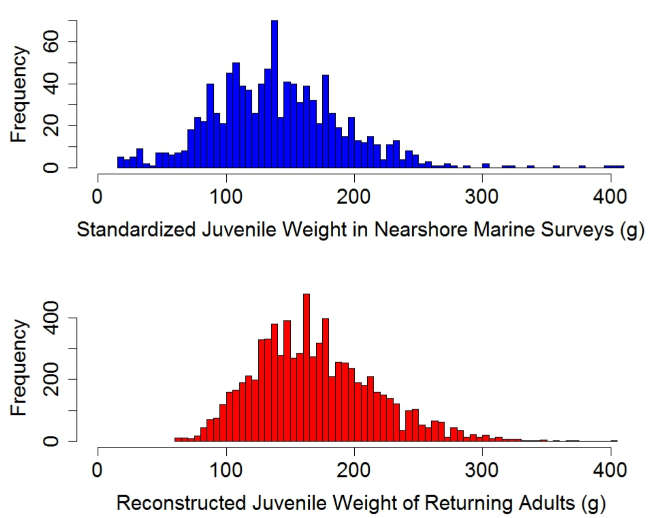

Fig. 4. Distribution of juvenile Chinook salmon weights (g) during September (2002-2007) in the northern Bering Sea and survivor weights reconstructed from adult scales collected at Pilot Station in the lower Yukon River.

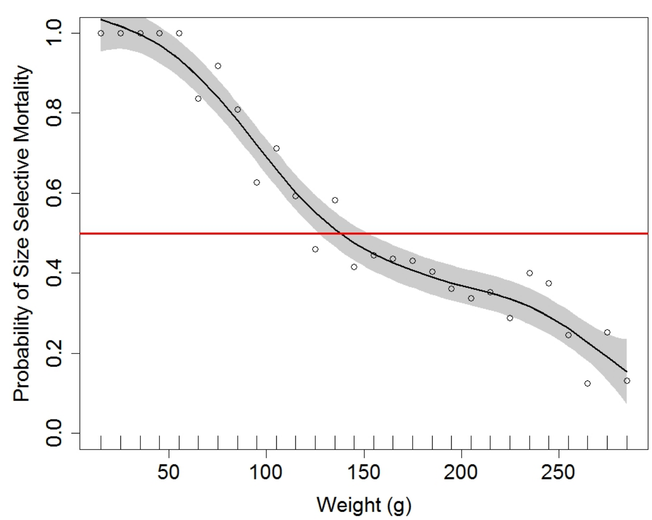

Fig. 5. A generalized additive model fit to size-selective mortality probability of juveniles collected during September (2002-2007) in the northern Bering Sea.

Although juvenile abundance and size were lower in colder years, juvenile distribution (average latitude) was the only feature of the juvenile population that differed significantly (Student's t-test $p = 0.01$, alpha = 0.05) between warm and cold years (Table 1). The absence of significance may reflect a greater dependency of juvenile abundance and size on freshwater and estuarine (local) processes not linked to broad-scale temperature patterns of the eastern Bering Sea. Marine distribution patterns of juveniles appear to have a closer linkage to broad-scale ecosystem patterns of the Bering Sea ecosystem and emphasize the potential negative impact that the loss of sea ice and warming of the Bering Sea could have on juvenile migration and survival. Although adult returns appear to be primarily a function of juvenile abundance and not juvenile survival, juvenile survival impacts the ability to use juvenile abundance as a leading indicator of future returns to the Yukon River

REFERENCES

ADFG (Alaska Department of Fish and Game). 2012. Chinook Gap Analysis. Alaska Chinook salmon Symposium. Anchorage, AK. (Available at: adfg.alaska.gov/static/home/news/hottopics/pdfs/gap_analysis.pdf)

Beamish, R. J., and Mahnken, C. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Prog Oceanogr. 49: 423–437.

Brett, J. R. and D. F. Alderdice. 1958. The resistance of cultured young chum and sockeye salmon to temperatures below 0°C. J. Fish. Res. Board Can. 15(5): 805-813.

Chambers, J, and T. Hastie. 1992. Statistical Models in S. Wadsworth and Brooks. Pacific Grove, California. 608 pp.

Danielson, S., K. Aagaard, T. Weingartner, S. Martin, P. Winsor, G. Gawarkiewicz, and D. Quadfasel. 2006. The St. Lawrence polynya and the Bering shelf circulation: New observations and a model comparison. J. Geophys. Res. 111: C09023.

Danielson, S., L. Eisner, T. Weingartner, and K. Aagaard. 2011. Thermal and haline variability over the central Bering Sea shelf: Seasonal and interannual perspectives. Cont. Shelf Res. 31:539-554.

Farley, E.V., Jr., and M. Trudel. 2009. Growth rate potential of juvenile sockeye salmon in warmer and cooler years on the eastern Bering Sea shelf. J. Mar. Biol. Vol. 2009, Article ID 640215. 10 pp.

Farley, E.V., Jr., J. Murphy J. Moss, A. Feldmm, and L. Eisner. 2009. Marine ecology of western Alaska juvenile salmon. *In* Pacific salmon: ecology and management of western Alaska's populations. *Edited by* C. C. Krueger and C. E. Zimmerman. Am. Fish. Soc., Symp. 70, Bethesda, Maryland. pp. 307-330.

Guthrie, C.M. III, S. Vulstek, H. Nguyen, J. Murphy, W. Templin, and J. Guyon. 2013. Genetic stock composition of juvenile Chinook salmon collected off the mouth of the Yukon River: Are these Yukon River fish? N. Pac. Anadr. Fish Comm. Tech. Rep. No. 9: 49. (Available at www.npafc.org)

Guyon, J, A. Gray, A. Celewycz, F. Thrower, T. Scott, W. Heard, and J. Joyce. 2013. Long term ocean survival trends of Chinook salmon released at Little Port Walter Marine Station in Southeast Alaska. N. Pac. Anadr. Fish Comm. Tech. Rep. No. 9: 239. (Available at www.npafc.org)

JTC (Joint Technical Committee of the Yukon River US/Canada Panel). 2013. Yukon River salmon 2012 season summary and 2013 season outlook. Alaska Department of Fish and Game, Division of Commercial Fisheries, Reg. Info. Rep. 3A13-01, Anchorage.

Moss, J.H., J.M. Murphy, E.V. Farley, L.B. Eisner, and A.G. Andrews. 2009. Juvenile pink and chum salmon distribution, diet, and growth in the northern Bering and Chukchi seas. N. Pac. Anadr. Fish Comm. Bull. 5: 191–196. (Available at www.npafc.org)

Murphy, J., O. Temnykh, and T. Azumaya. 2003. Trawl comparisons and fishing power corrections for the *F/V Northwest Explorer*, *R/V TINRO*, and *R/V Kaiyo Maru* during the 2002 BASIS Survey. N. Pac. Anadr. Fish Comm. Doc. No. 677. 25 pp. (Available at www.npafc.org)

Murphy, J.M., W.D. Templin, E.V. Farley, Jr., and J.E. Seeb. 2009. Stock-structured distribution of western Alaska and Yukon juvenile Chinook salmon (*Oncorhynchus tshawytscha*) from United States BASIS surveys, 2002–2007. N. Pac. Anadr. Fish Comm. Bull. 5: 51–59. (Available at www.npafc.org)

Myers, K.W., R.V. Walker, N.D. Davis, and J.L. Armstrong. 2009. High seas distribution, biology, and ecology of Arctic-Yukon-Kuskokwim salmon: Direct information from high seas tagging experiments, 1954-2006. Am. Fish. Soc. Symp. 70: 201-239.

NPAFC (North Pacific Anadromous Fish Commission). 2001. Plan for NPAFC Bering-Aleutian Salmon International Survey (BASIS) 2002-2006. N. Pac. Anadr. Fish Comm. Doc 579, Rev. 2. 27 pp. (Available at www.npafc.org)

Pella, J. and M. Masuda. 2001. Bayesian methods for analysis of stock mixtures from genetic characters. Fish. Bull. 99, 151-167.

Stabeno, P.J., E.V. Farley, N.B. Kachel, S. Moore, C.W. Mordy, J.M. Napp, J.E. Overland, A.I. Pinchuk, M.F. Sigler. 2012. A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. Deep-Sea Res. II: 65-70: 14-30.

Stram, D.L., and J.N. Ianelli. 2009. Eastern Bering Sea pollock trawl fisheries: variation in salmon bycatch over time and space. *In* Pacific salmon: ecology and management of western Alaska's populations. *Edited by* C. C. Krueger and C. E. Zimmerman. Am. Fish. Soc., Symp. 70, Bethesda, Maryland. pp. 827-850

Templin, W.D., L.W. Seeb, J.M. Murphy, and J.E. Seeb. 2011a. Stock-specific forecast of AYK Chinook salmon. 2011 Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative Project Final Product. (Available at www.aykssi.org/projects/)

Templin, W.D., J.E. Seeb, J.R. Jasper, A.W. Barclay, and L.W. Seeb. 2011b. Genetic differentiation of Alaska Chinook salmon: the missing link for migratory studies. Mol. Ecol. Resources 11: 226-246.